High Pressure Gas Filled Cavities for Use in Muon Accelerators

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Acknowledgement

Muons, Inc.

Muon Accelerator Program

- For this talk, I have drawn on material, either directly or indirectly, presented by:
  - Mark Palmer, Katsuya Yonehara, Moses Chung, Frank Marhauser, Patrick Huber, Mauricio Lopes, Kwangmin Yu, …

Thank you.

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Muon Accelerator Program

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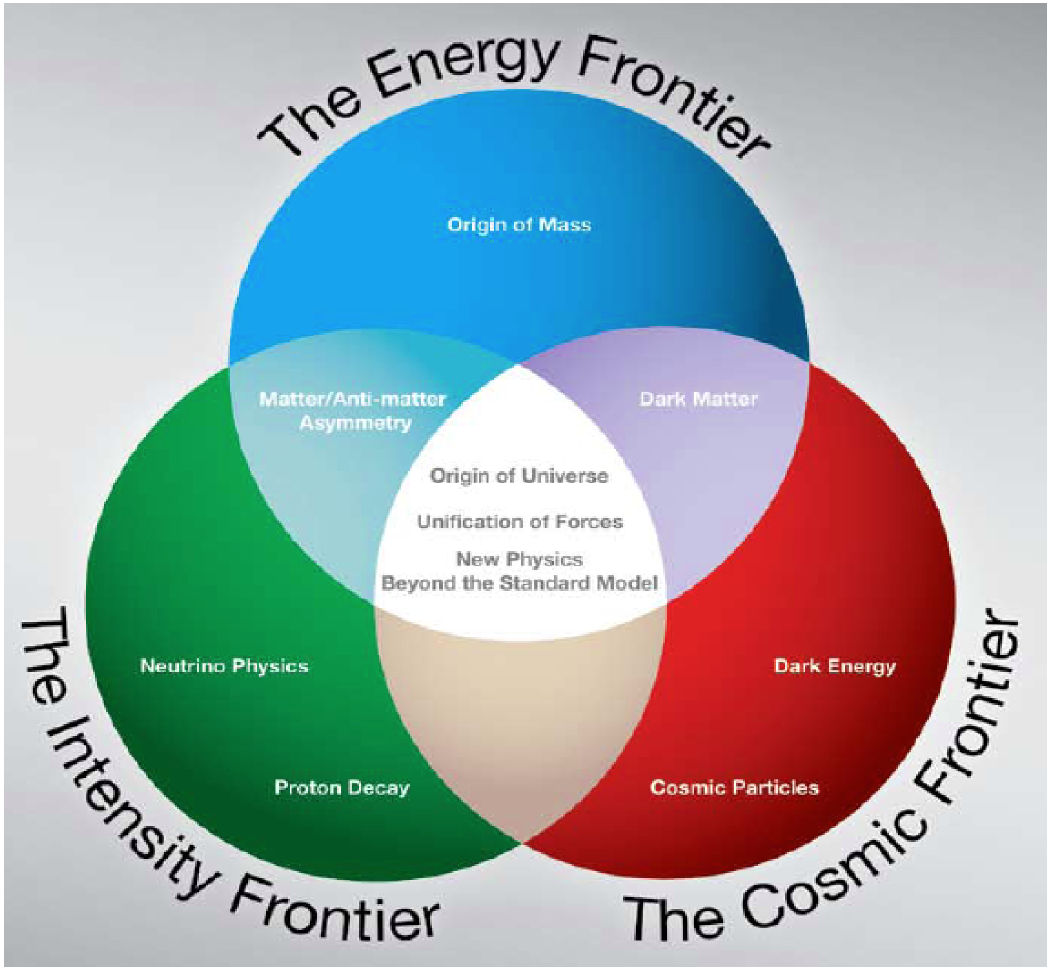
- The US Muon Accelerator Program (MAP) grew out of the Neutrino Factory Muon Collider Collaboration (NFMCC, circa 1996) and was established in March 2011
  - "...to develop and demonstrate the concepts and critical technologies required to produce, capture, condition, accelerate and store intense beams of muons for Muon Colliders and Neutrino Factories."
  - The goal of MAP is to deliver results by the end of the decade that will permit the high energy physics community to make an informed choice of the optimal path to a high energy lepton collider and/or a next-generation neutrino beam facility.

Multiple Frontiers

- Muon accelerator R&D is focused on developing a facility that can address critical questions spanning two frontiers…
- The Intensity Frontier:
  - A Neutrino Factory producing well-characterized neutrino beams for precise, high sensitivity studies
  - Includes a short baseline (nuSTORM) and long baseline (IDS-NF, NuMAX)
- The Energy Frontier:
  - A Muon Collider capable of reaching multi-TeV center of mass energies
  - A Higgs Factory on the border between these frontiers



[Courtesy of M. Palmer]

Physics Motivations

- Muon beams offer enormous potential for high energy physics
  - Tests of Lepton Flavor Violation
  - Anomalous magnetic moment – hints of new physics (g-2)
  - Equal fractions of electron and muon neutrinos for high intensity neutrino experiments

$$\mu^+ \rightarrow e^+ \, \nu_e \, \bar{\nu}_\mu \qquad \mu^- \rightarrow e^- \, \bar{\nu}_e \, \nu_\mu$$

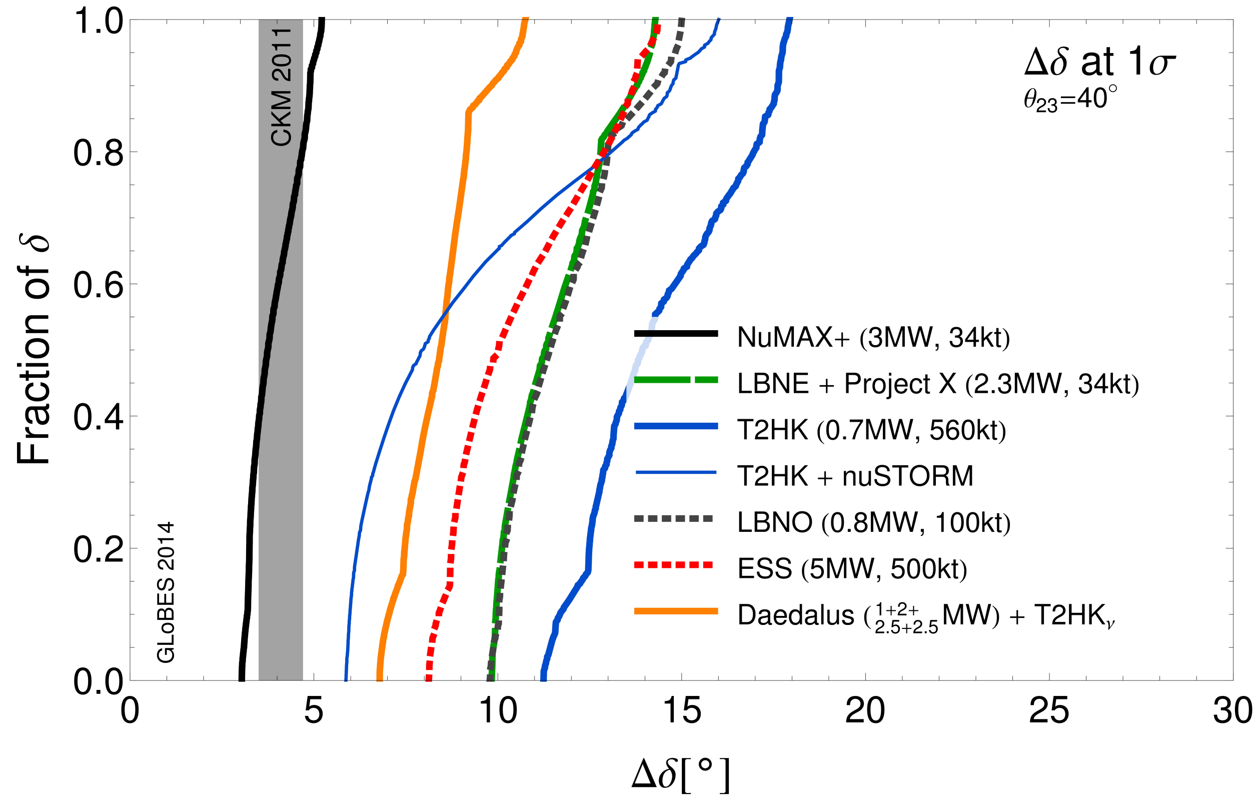
  - Large coupling to the "Higgs mechanism"

$$\sigma \propto \left(\frac{m_\mu^2}{m_e^2} \right) \approx 4\text{x}10^4$$

  - Extremely precise probe of fundamental interactions (as with e^+e^- colliders, as opposed to hadron colliders)

Neutrino Factory Physics

- Neutrino physics that could come out of a Neutrino Factory include:
  - CP violation
  - Mass hierarchy
  - θ_{23} (=, <, > $\pi/4$)
  - Probe new physics



[Courtesy of P. Huber]

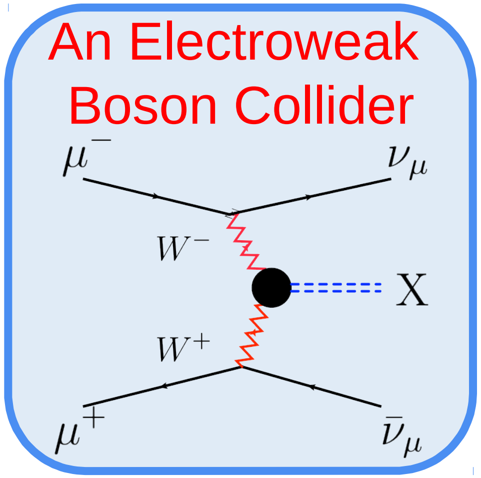
Muon Collider Physics

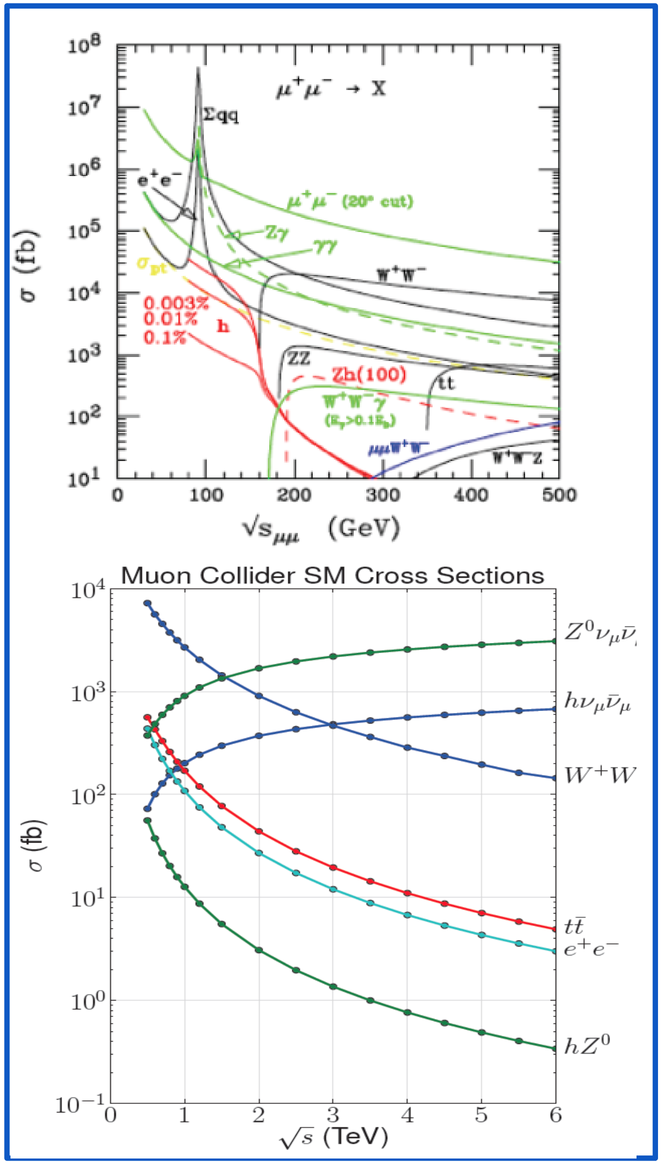
- Physics at multiple center of mass energies is possible:
- √s < 500 GeV
  - Higgs Factory (126 GeV)
  - Standard Model thresholds (Z^0h, W^+W^-, top pairs)
  - Excellent δE/E (few $\times10^{-5}$)
- √s > 500 GeV
  - Sensitive to physics beyond the Standard Model
  - Fusion processes dominate for a multi-TeV collider

$$\sigma(s) = C \ln\left(\frac{s}{M_x^2}\right) + \ldots$$

  - A 10 TeV $\mu^+\mu^-$ collider has comparable electro-weak discovery potential as a 70 TeV pp collider

[Courtesy of E. Eichten]





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A Muon Accelerator

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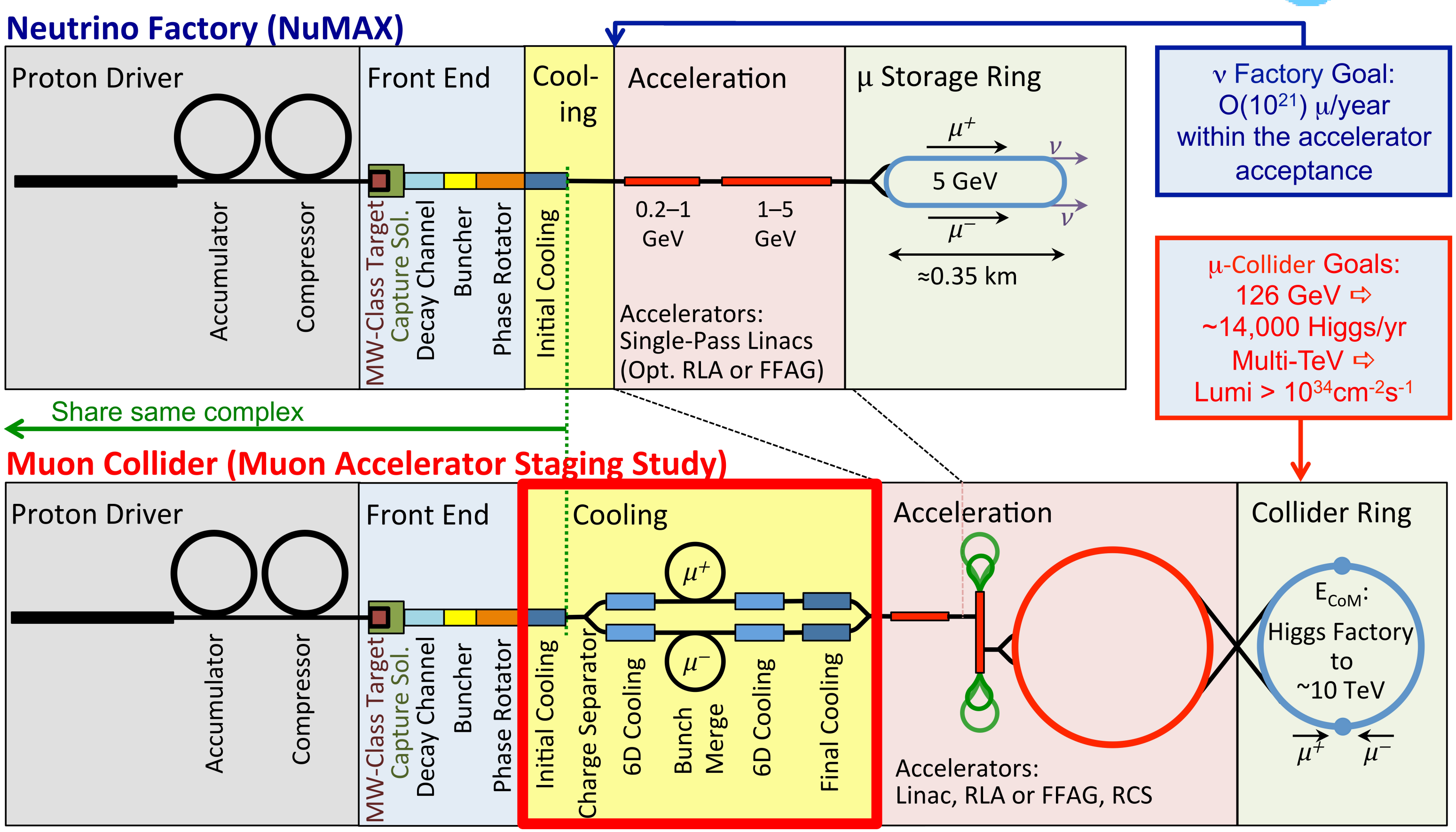
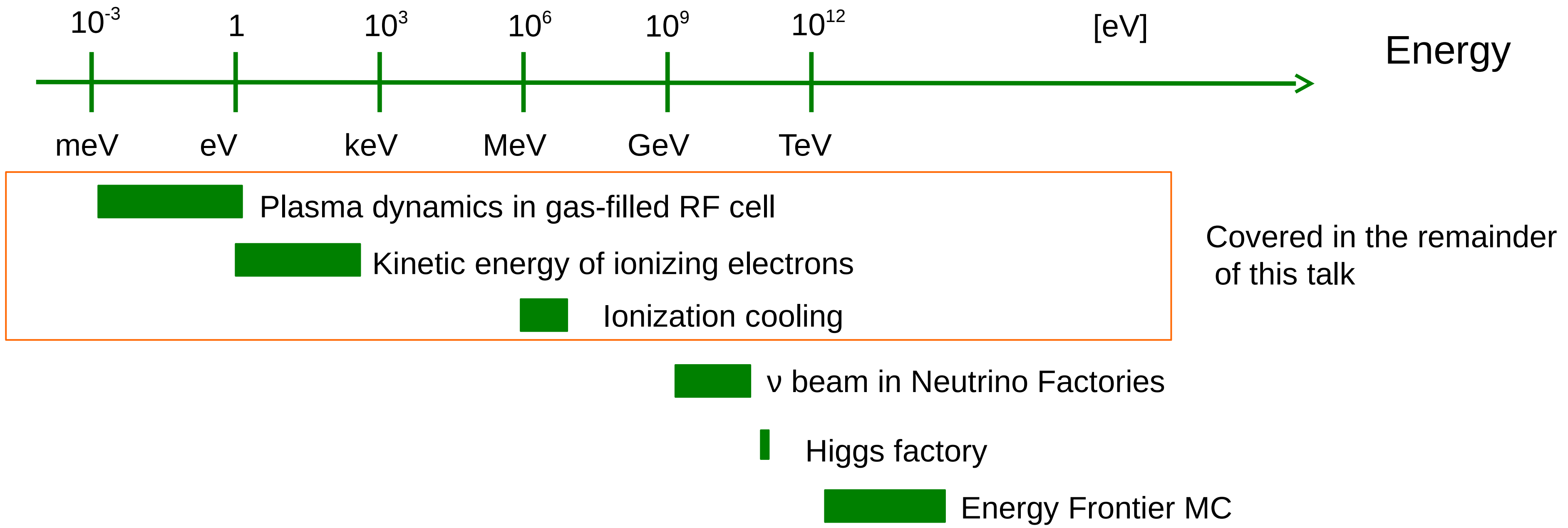


- The major challenge in building a muon accelerator is cooling a beam of muons within an acceptable amount of time
- There is one method and two designs being pursued to do this:
  - Vacuum cooling channel
  - High pressure gas cooling channel

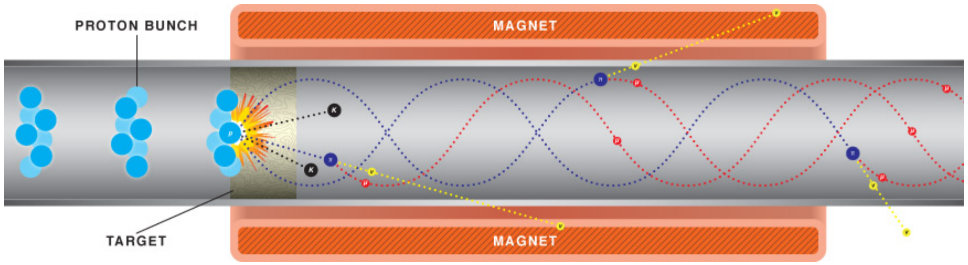
Energy Scale

- Muon accelerators based on high pressure gas filled RF cavities cover a wide range of energies

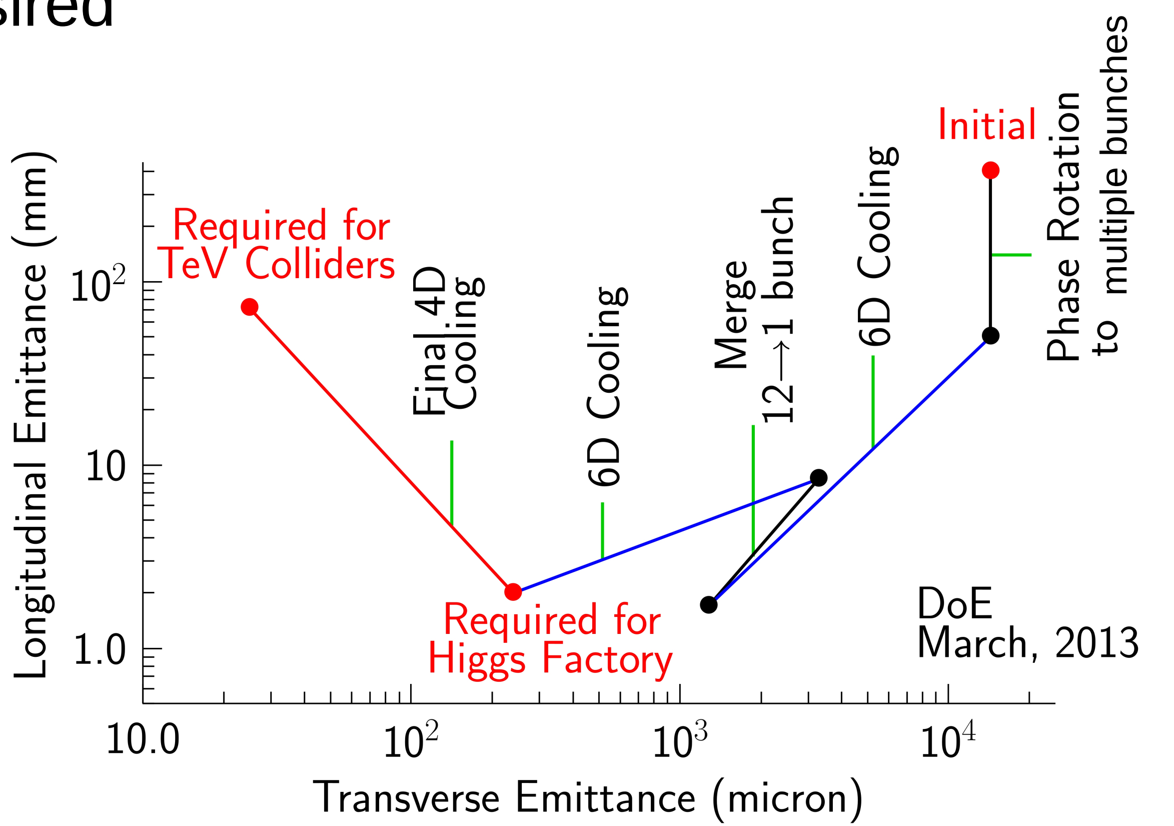


Emittance

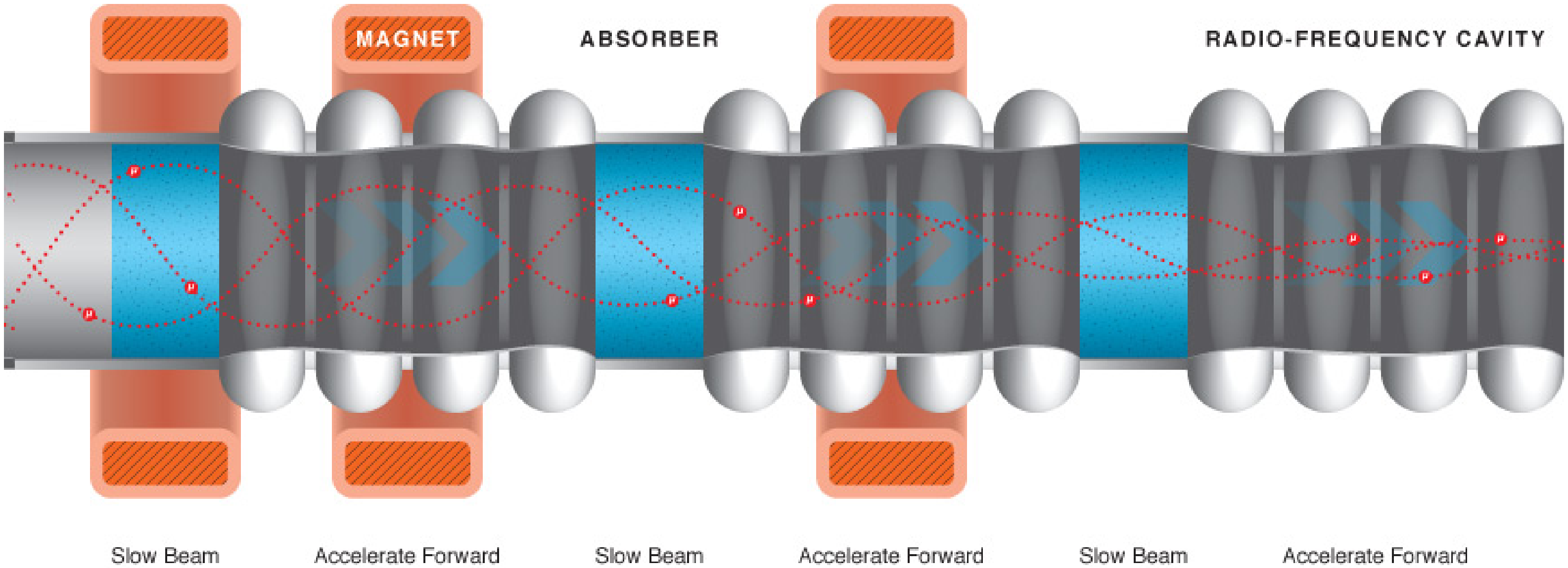
- After colliding a proton beam with a target, the resulting pions are allowed to decay to muons



- The initial emittance is much too large to attain the desired luminosity
- For a Higgs Factory, a momentum spread on the order of 10^{-5} mandates small longitudinal emittance
- For a TeV collider, the transverse emittance must be reduced even further

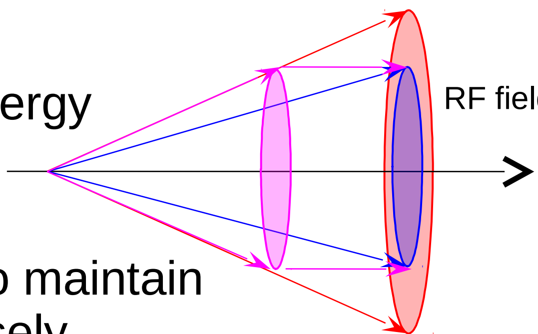


Ionization Cooling – I

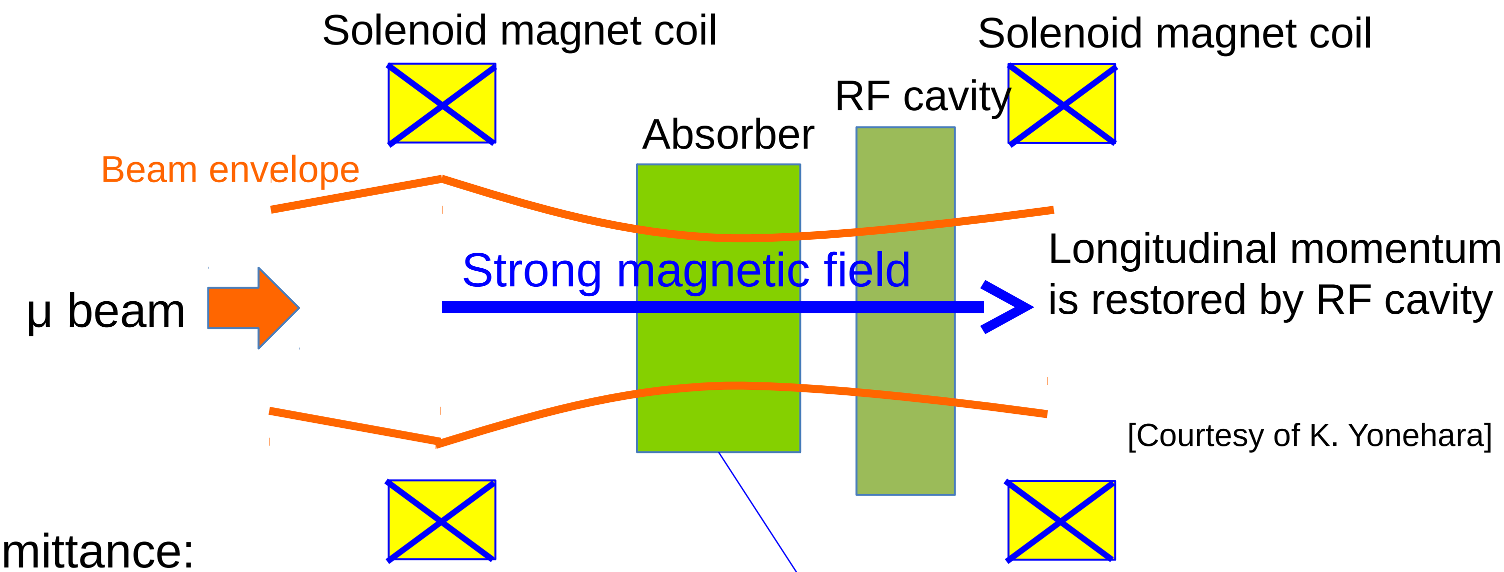


- The only means of cooling the beam fast enough is ionization cooling
- Emittance is a measure of position and angle
- The beam passes though an absorbing material, losing energy
  - Changes the angle, but not position
- RF cavities then replace the lost longitudinal momentum to maintain energy along the beam path, while losing energy transversely
- Repeated many times, this reduces the emittance in the transverse dimension (4D cooling)

[Courtesy of K. Yonehara]



Ionization Cooling – II



Change in normalized emittance:

$$\frac{d\epsilon_n}{ds} = \frac{1}{\beta^3}\frac{\beta_\perp (0.014)^2}{2 E_\mu m_\mu X_0} - \frac{1}{\beta^2}\left\langle \frac{d E_\mu}{ds} \right\rangle \frac{\epsilon_n}{E_\mu}$$

$$\beta_\perp = \frac{\pi \sigma_\perp^2}{\epsilon_\perp}$$

- To minimize heating, a small beta function (i.e. strong magnetic field) and large radiation length are desirable
  - i.e. large angular spread in the beam
- To maximize cooling, a large stopping power (dE/ds) is desirable
- Hydrogen provides ideal radiation length and stopping power

A Problem, and a Solution

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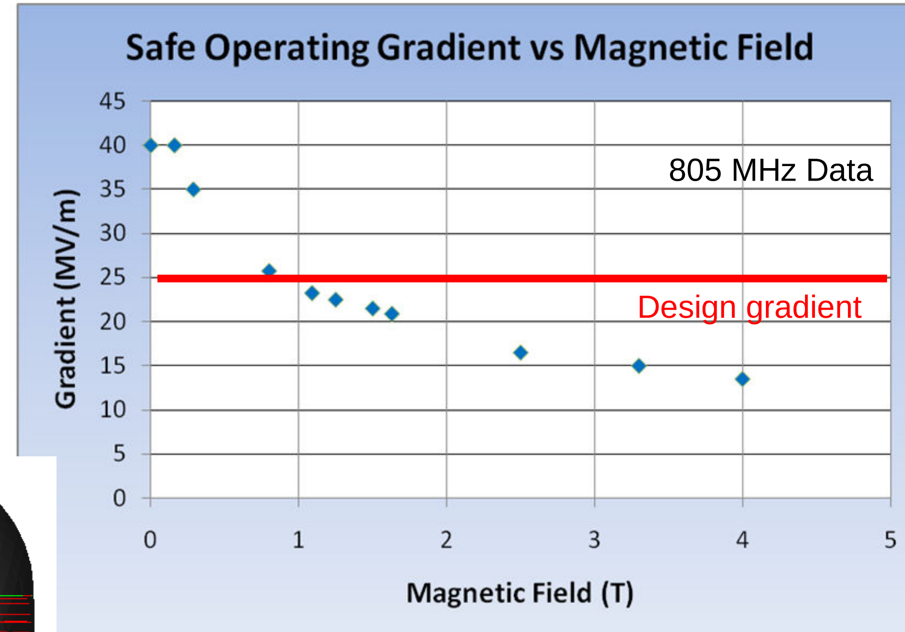
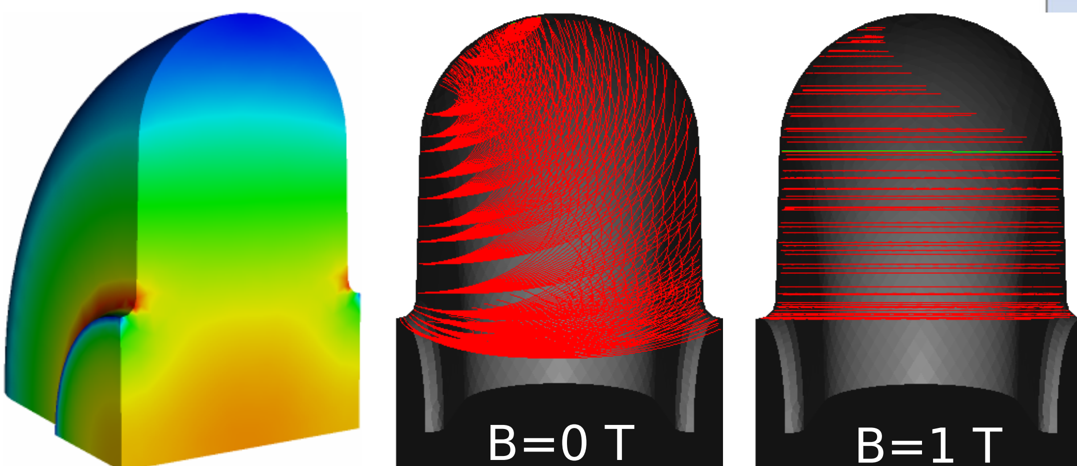
- Early results have shown vacuum pillbox RF cavities to break down in strong external magnetic fields
- This is likely due to field emission electrons being focused onto a small region of the opposing wall



Simulation



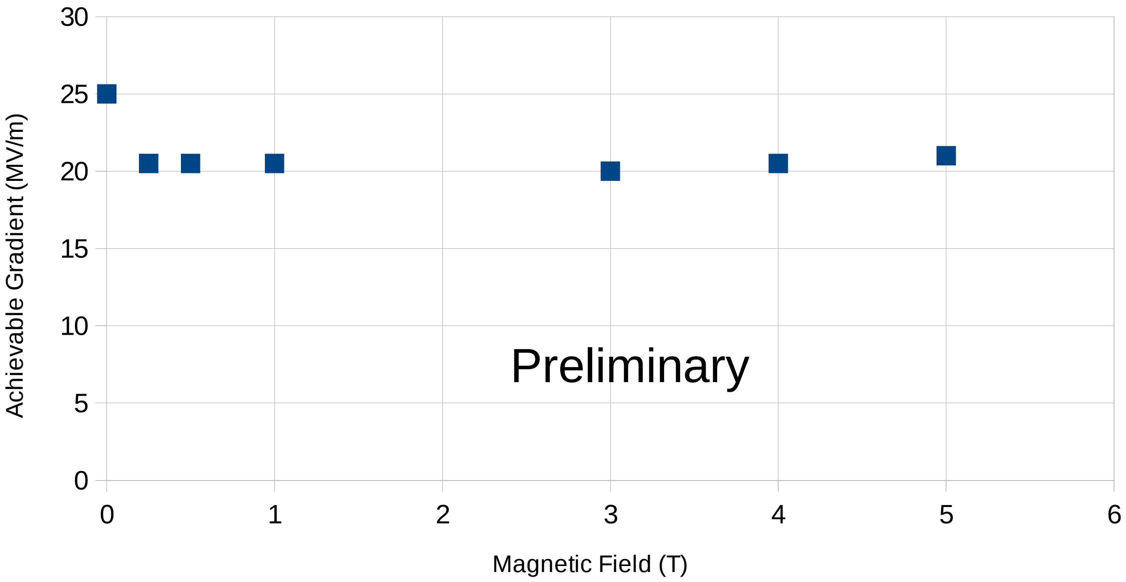
E field contour

- There are two ways to combat this
  - Limit field emission
  - Limit the effect of field emission

- This talk will focus on the latter – namely preventing field emission electrons from becoming a problem by filling the cavity with a high pressure gas

An Aside

- Progress is being made on the vacuum front
- A number of techniques to limit field emission are being pursued:
  - Material studies (Cu vs Be, ...)
  - Surface coatings (TiN, …)
  - Cavity geometry
- Recent results from an 805 MHz vacuum pillbox cavity look promising
- A modular 805 MHz pillbox cavity is being fabricated to investigate the above techniques



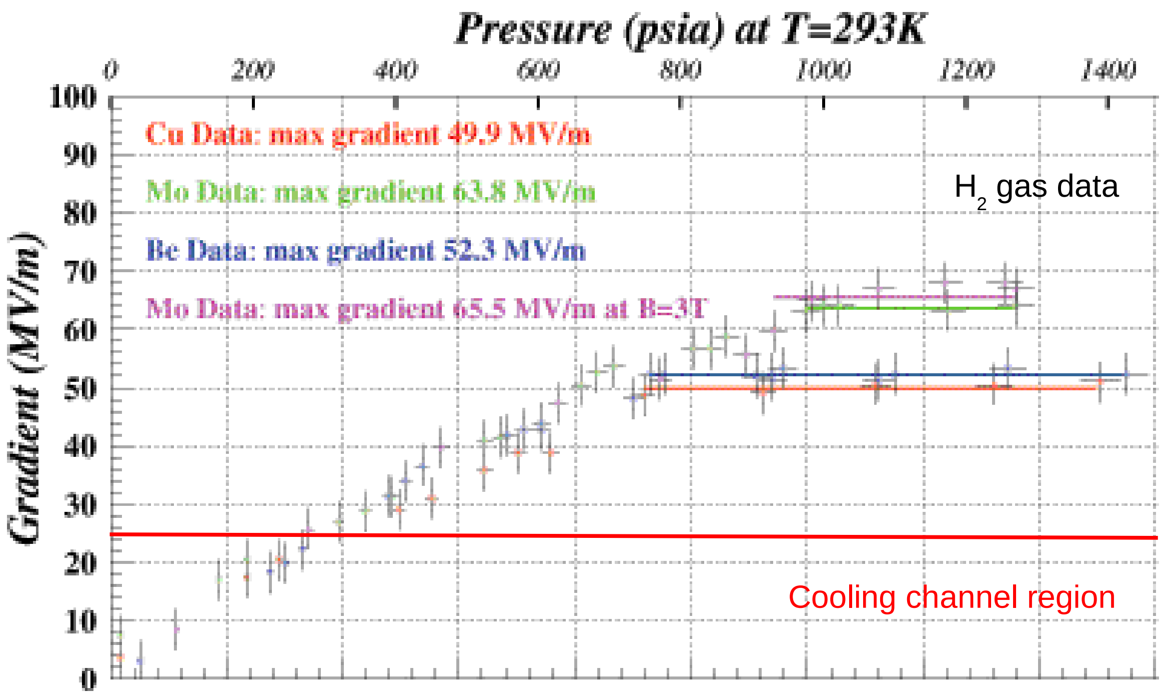
Breakdown in Gas Filled Cavities

- Field emission electrons are the source of breakdown in vacuum cavities
- For gas filled cavities, electrons:
  - Gain energy from the electric field (E)
  - Lose energy through collisions with molecules (gas Pressure)
- The ratio E/P determines how much energy an electron gains between collisions
  - Doubling the electric field and gas pressure produces the same energy gain
- Above a certain electric field strength, an electron may gain enough energy to ionize the gas
  - Produces a cascade of electrons and causes breakdown – this is called gas breakdown

Encouraging Results

- Studies have verified the breakdown physics in a gas filled cavity
  - Increasing the gas pressure increases the breakdown gradient – to a point
  - After which, breakdown is dependent on material properties rather than gas properties

- Results show virtually no difference in breakdown gradient between no magnetic field and 3 T
- Cavities in an actual cooling channel will be operated far below the breakdown limit



P. Hanlet et al, Proceeding of EPAC '06, TUPCH147

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MuCool Test Area

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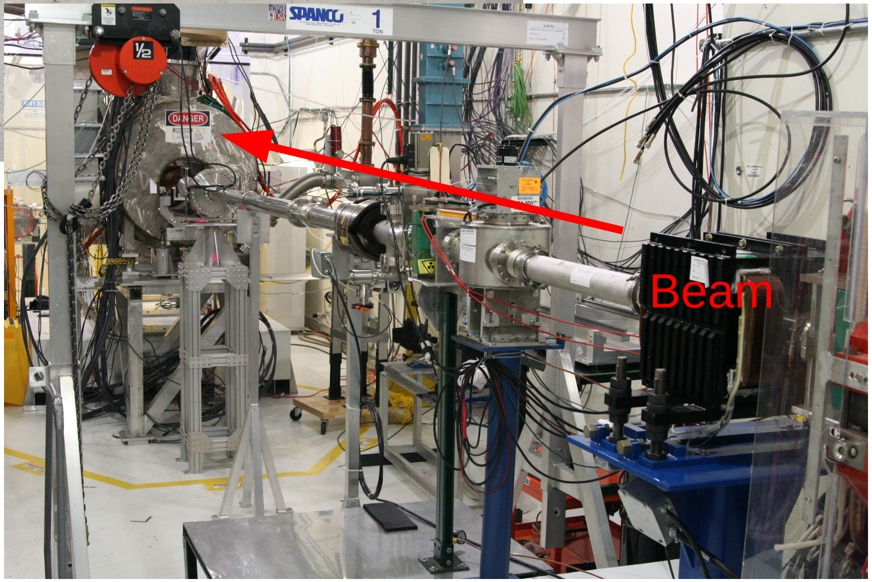
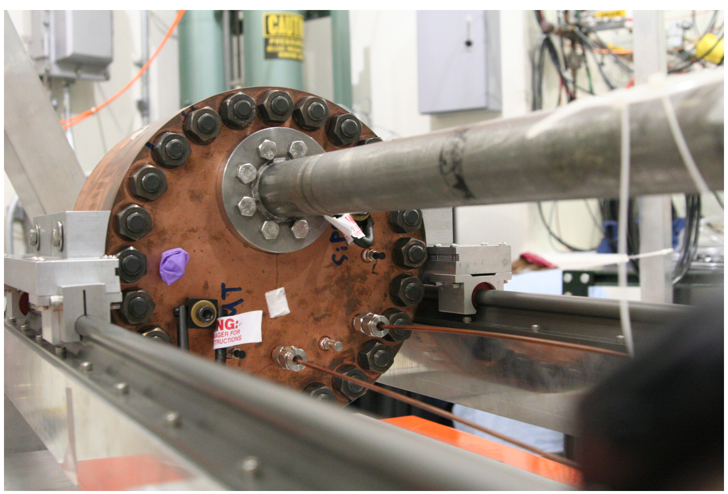
Muon Accelerator Program

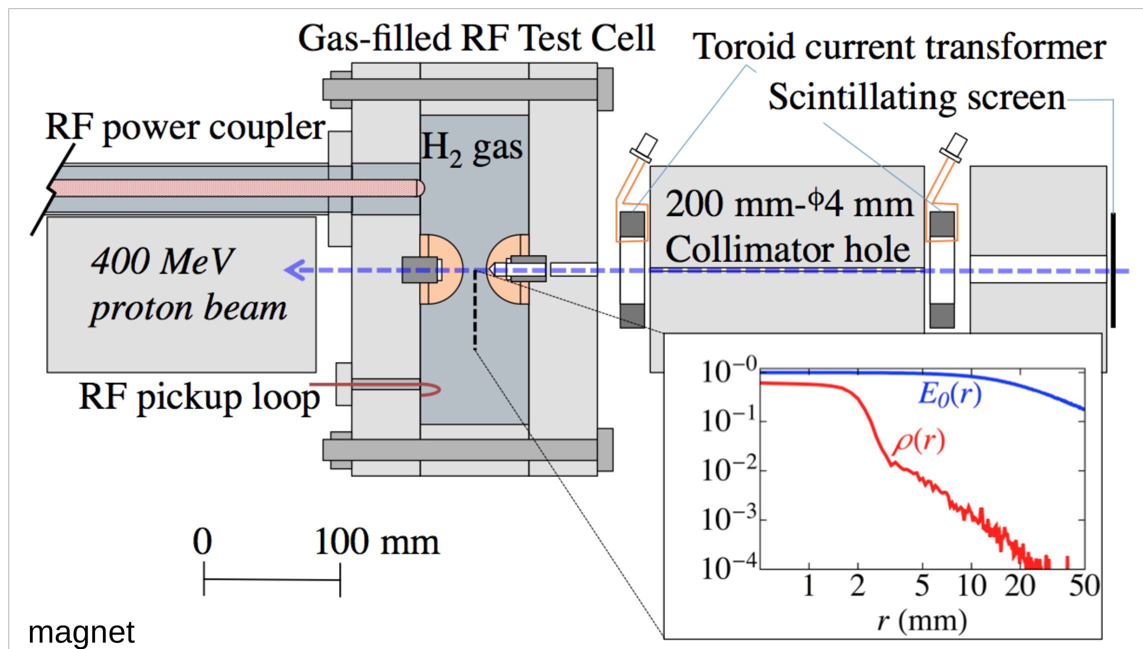
- Currently, the goal of the MuCool Test Area is to provide a solution for the problem of operating high gradient RF cavities in strong external magnetic fields
- The facility is located at the end of the Fermilab linac and makes use of a dedicated beamline
- The MTA is equipped with an array of diagnostic equipment
  - RF pickup probes
  - Directional couplers
  - PMTs, SiPMs
  - Radiation monitors
  - Multiwires/BPMs
  - Beam current monitors
  - Scintillating screen/CCD camera



Beam Test

- A beam test at the MTA was performed to evaluate the performance of a cavity subject to an intense beam
- Various gas species, gas pressures, and electric fields were tested, both with and without a 3 T magnetic field
  - H_2, D_2, N_2, He, Dry Air, SF_6
  - 20 – 100 atm
  - 5 – 50 MV/m
- Measurements of the plasma dynamics and evolution were made in order to predict how a cavity would operate in a real cooling channel

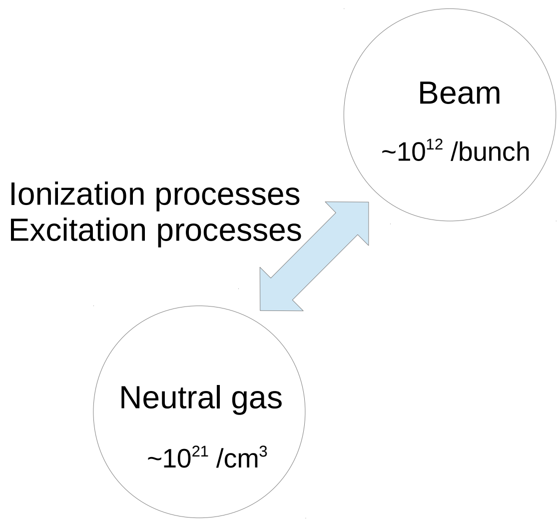




Beam Test Overview

- A beam passing through a gas filled cavity will ionize the gas
- The resulting plasma will be shaken by the RF electric field and transfer energy from the cavity to the gas (electrons are the main contributors due to their small mass)
- Electrons may recombine with positive ions, however this process is not fast enough and there is too much energy loss
- The addition of an electronegative dopant gas sucks up the electrons quickly, greatly decreasing the energy loss
- Remaining positive ions continue to load the cavity, but do neutralize, albeit slowly

Beam – Neutral Gas



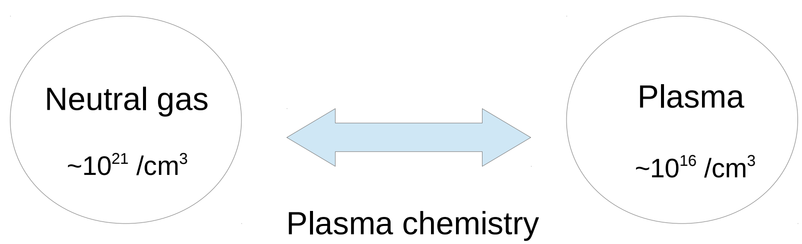
- A beam of muons traversing a HPRF cavity will excite and ionize the gas
- The amount of ionization can be measured directly from the beam current and momentum, gas species and density, and the average amount of energy required to ionize a molecule

$$N_{pairs} = \frac{\frac{dE}{dx}\rho L}{W_i} N_\mu$$

- For a cooling channel cavity, each 200 MeV muon will produce ~2,000 electron-ion pairs per cm

Plasma – Neutral Gas I

- Won't the ionization electrons short the cavity?
  - No, collisions with neutrals (10^5 x higher density) prevents this
- At 100 atm, electrons make roughly 30 collisions / picosecond
- Quickly come into thermal equilibrium (~10 ps) above the gas temperature
- After which, electrons drift with the applied electric field (drift velocity is a fraction of the thermal velocity)
- The hydrogen ions quickly (~ 1 ps) form hydrogen clusters (H_3^+, H_5^+, …)
- Ions also drift with the RF field, but never come out of thermal equilibrium with the gas



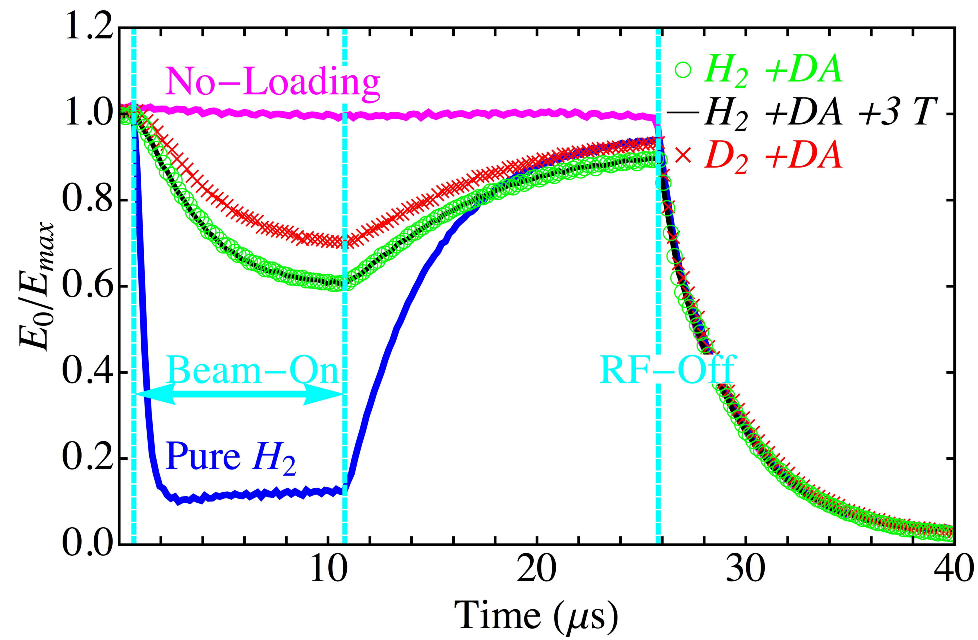
Plasma – Neutral Gas II

- Through collisions, electrons (and ions) transfer energy from the cavity to the gas
- We call this energy transfer plasma loading

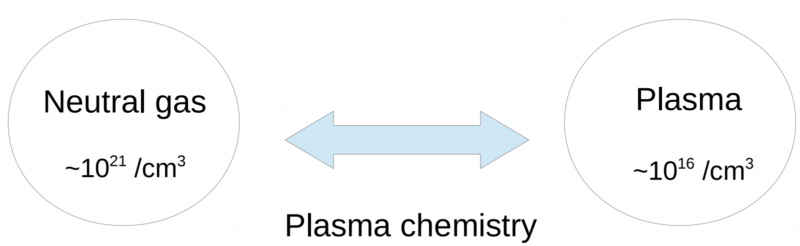
$$dw = q \int v \; E(t) \; dt = q \int \mu \; E^2(t) \; dt$$

q = charge, μ = mobility, E = electric field, v = drift velocity

- For a gas filled cavity to work in practice, this loading must be manageable



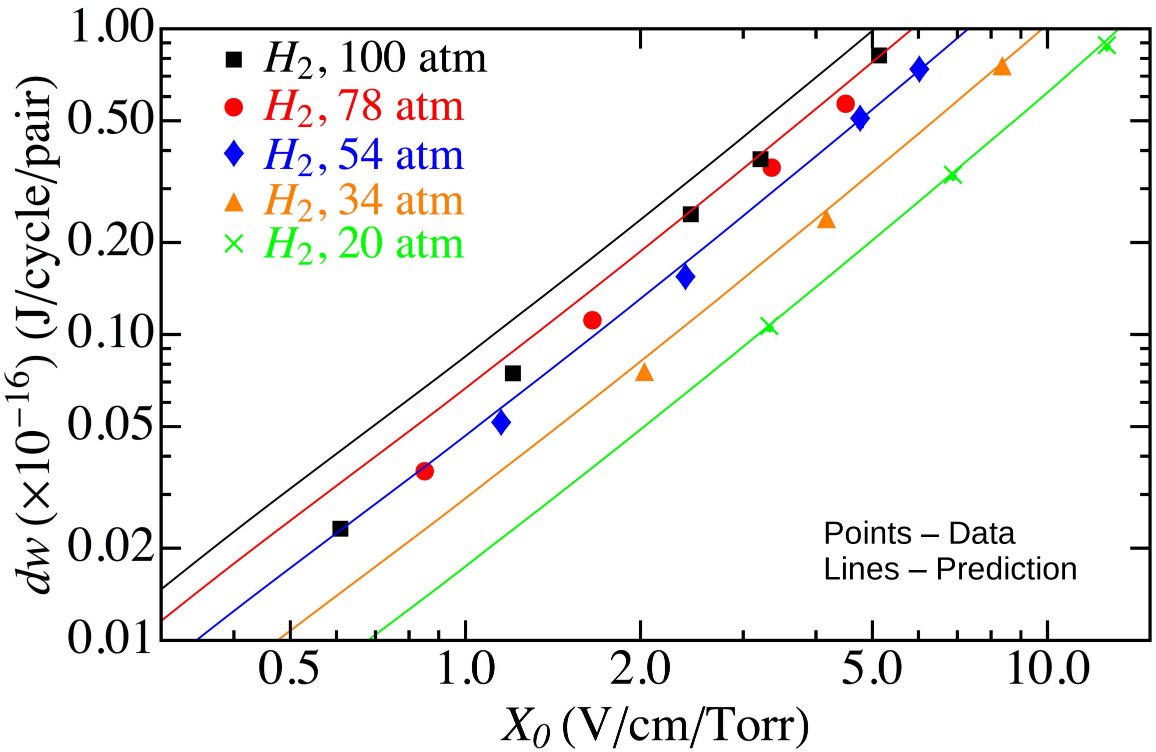
M. Chung et al, Phys. Rev. Lett. 111, 184802 (2013)



Energy Dissipation

- Measurements taken at the MTA of the energy loss due to each electron-ion pair over one RF cycle
  - ~10^{-17} J for electrons
  - ~10^{-19} J for ions

- Energy loss measurements show a pressure dependence
- This is a beneficial effect – smaller plasma loading than predicted based on low pressure DC measurements
- Can be attributed to multiple scattering and the formation of briefly bound states of H_2^-



M. Chung et al, Phys. Rev. Lett. 111, 184802 (2013)

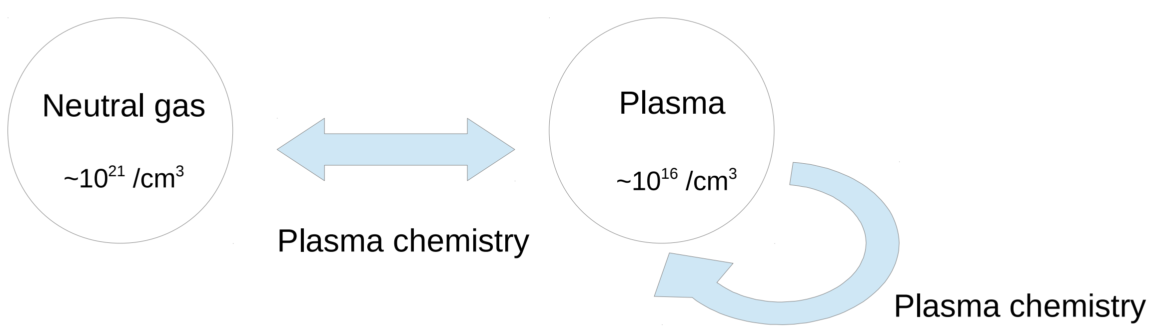
Plasma Chemistry

- There are three processes that are of interest for determining the plasma evolution:
  - Electron attachment to oxygen (τ)
  - Electron recombination with hydrogen (β)
  - Hydrogen recombination with oxygen (η)
- A set of rate equations can be set up to describe these:

$$\frac{dn_e}{dt} = \dot{n}_e - \beta n_e n_H - \frac{n_e}{\tau} \qquad \frac{dn_H}{dt} = \dot{n}_H - \beta n_e n_H - \eta n_H n_O \qquad \frac{dn_O}{dt} = \frac{n_e}{\tau} - \eta n_H n_O$$

Electron attachment time = τ, Electron-hydrogen recombination rate = β, Hydrogen-oxygen recombination rate = η

- Measurements of τ, β and η will allow us to predict the evolution of the plasma



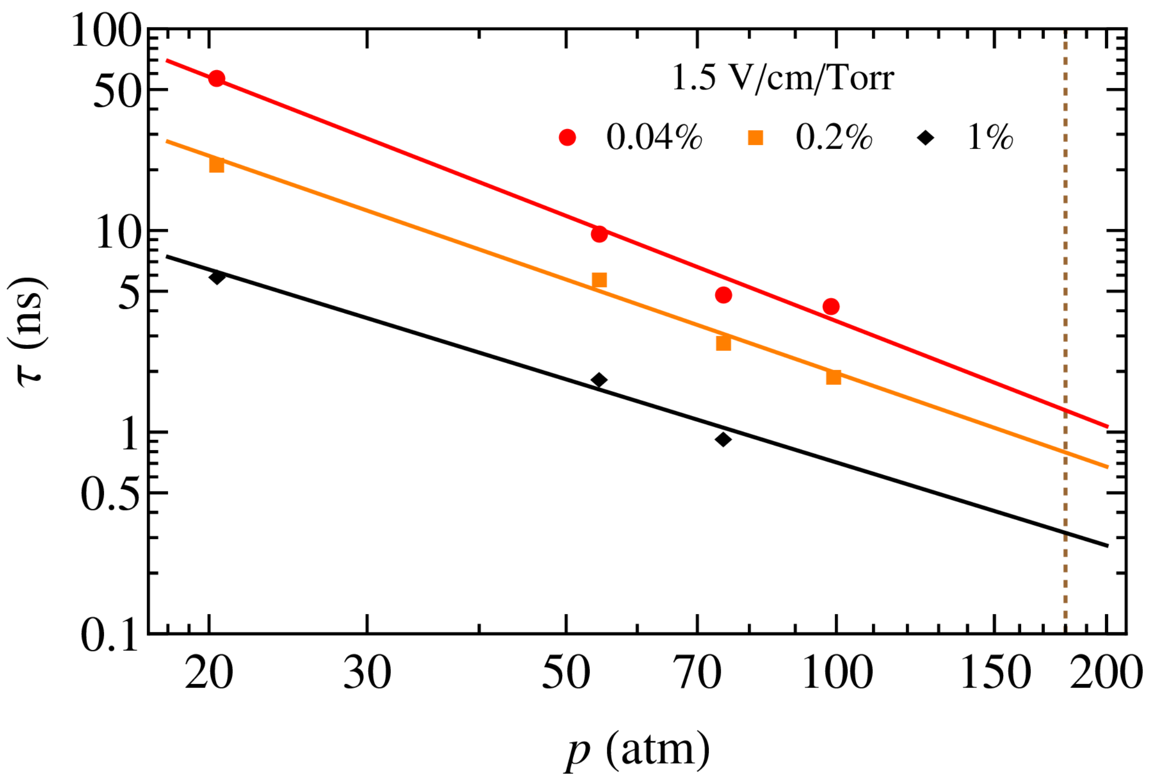
Electron Recombination

- Electrons may recombine with the various hydrogen clusters (H_3^+, H_5^+, H_7^+, …)
  - This process is often dissociative $e^- + H_3^+ \rightarrow H + H_2$
- Hydrogen species ratio depends on gas pressure
- Measurements made during the beam test did not include spectroscopy, and so the overall recombination rate was measured
- Ranges from 10^{-7} to 10^{-6} cm^3/s and increases with gas pressure
  - Indicates H_5^+ is the dominant positive ion
- Not fast enough to remove electrons before significant plasma loading occurs

Electron Attachment

- One way to remove electrons (and minimize plasma loading) is to dope with an electronegative gas so that they may become attached
- This is a three body process: $e^- + O_2 \rightarrow O_2^{-*}$

$$O_2^{-*} + M \rightarrow O_2^- + M$$



M. Chung et al, Phys. Rev. Lett. 111, 184802 (2013)

- Measurements of the attachment time as a function of pressure indicate that at 180 atm with 0.2% O_2, $\tau < 1$ ns
- This prevents a build up of electrons due to the next beam bunch arriving 3 ns later

Ion Recombination

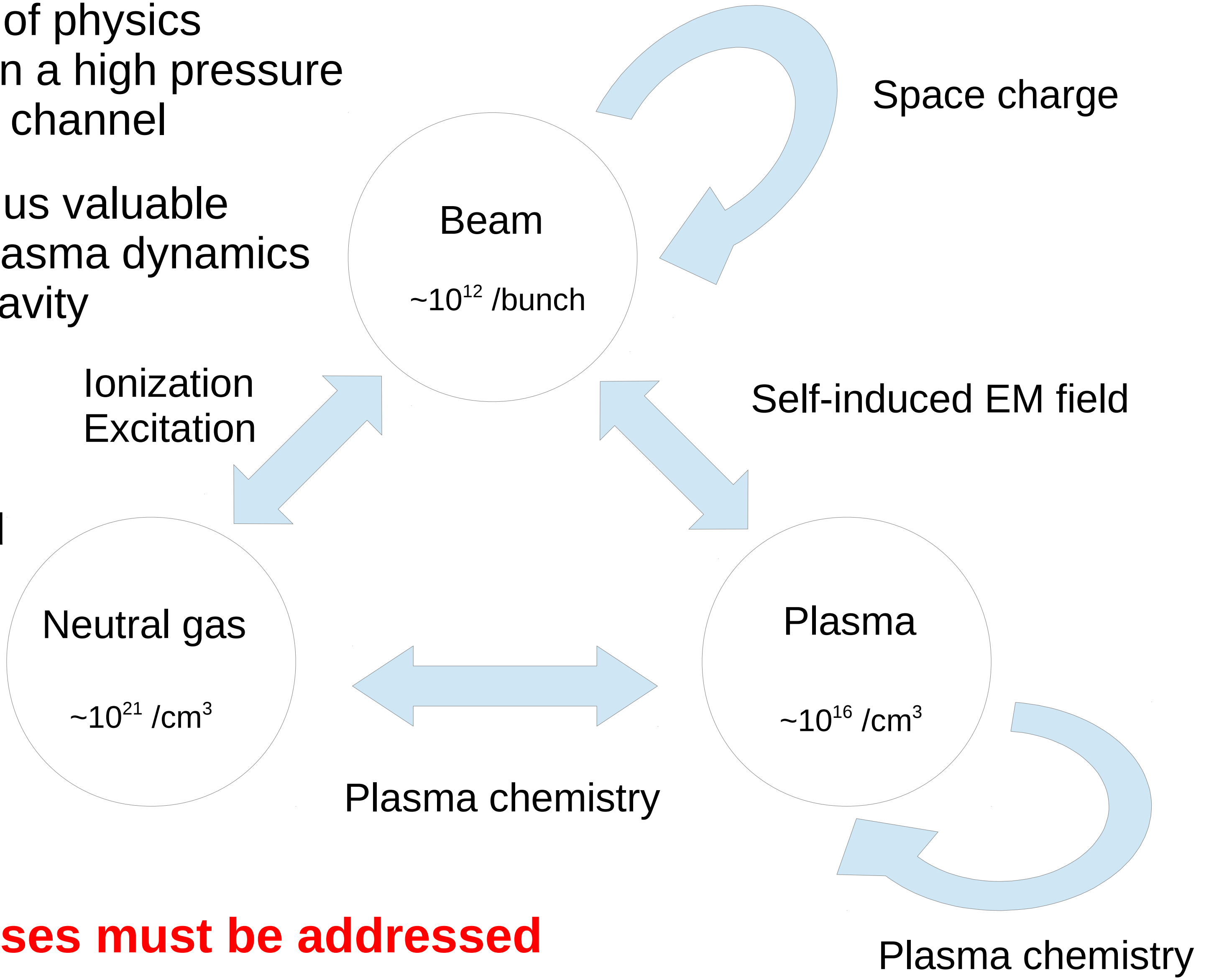
- Hydrogen clusters and negative oxygen (O_2^-, O_3^-, …) may "recombine" (neutralize)
- As with electron recombination, our measurements do not permit us to distinguish the ion species involved
  - Measurements of hydrogen-oxygen recombination do not exist in the Literature
- Overall recombination rate measured ranges from 10^{-8} to 10^{-7} cm^3/s and decreases with gas pressure
  - This is consistent with past measurements of similar ions
- The majority of ions will survive over the course of a beam pulse (60 ns)
- In a cooling channel, this appears to be the dominant source of plasma loading

What We've Learned

- The beam test at the MTA provided critical information about:
  - The energy dissipation of electrons and ions (10^{-17} J/cycle e^-, 10^{-19} J/cycle ions)
  - The attachment time of electrons to oxygen (< 1 ns – few 100 ns)
  - The recombination rate of electrons with hydrogen (10^{-7} – 10^{-6} cm^3/s)
  - The recombination rate of hydrogen and oxygen ions (10^{-9} – 10^{-8} cm^3/s)
- The effect of increasing gas density on energy dissipation is not as severe as originally predicted
- Higher plasma densities increase the rate of recombination
- Electrons are removed very quickly through attachment, and at high densities, through recombination
- Due to their smaller recombination rate, ions appear to be the dominant contributors to plasma loading at high gas densities and beam intensities

Physics Processes

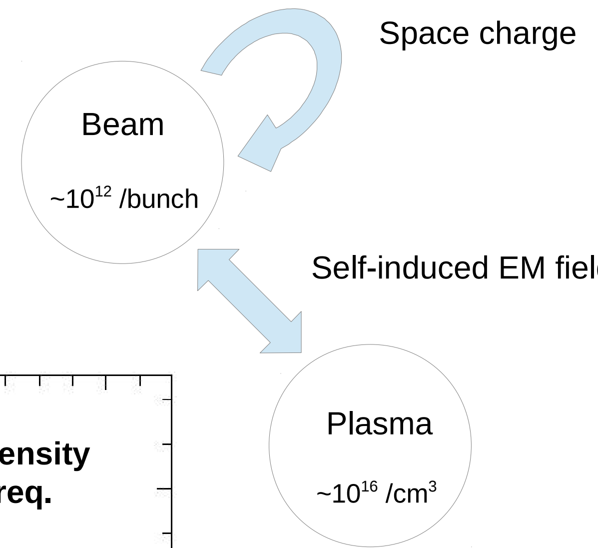
- There are a number of physics processes involved in a high pressure gas filled RF cooling channel
- The beam test gave us valuable information on the plasma dynamics and effect on a RF cavity
- Effects of space charge and beam-plasma interaction must be investigated
- This relies on simulation efforts



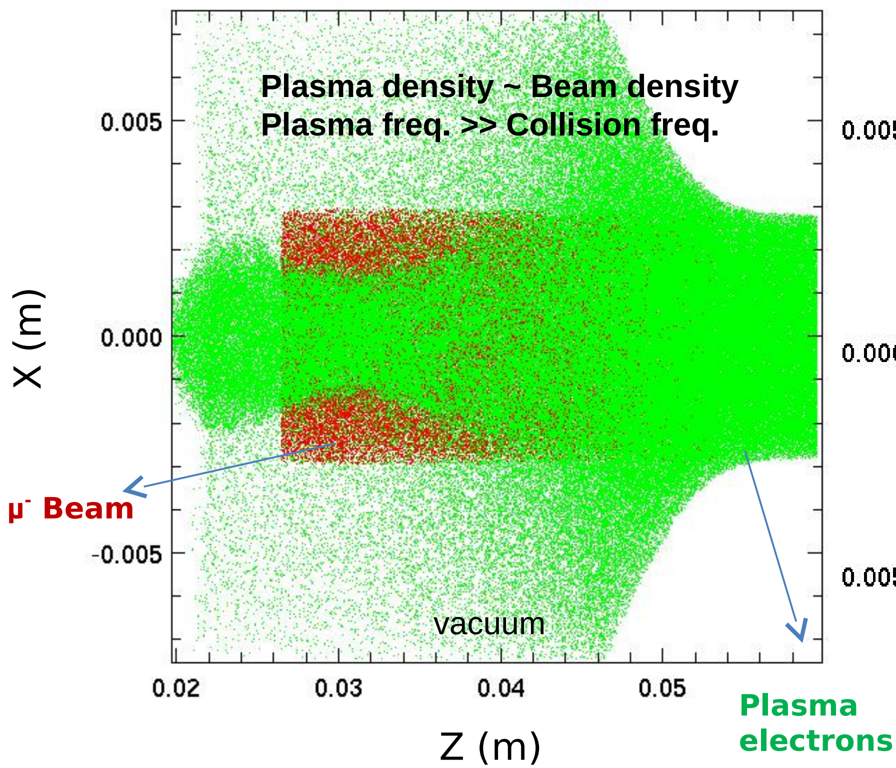
All of these processes must be addressed

Beam – Plasma

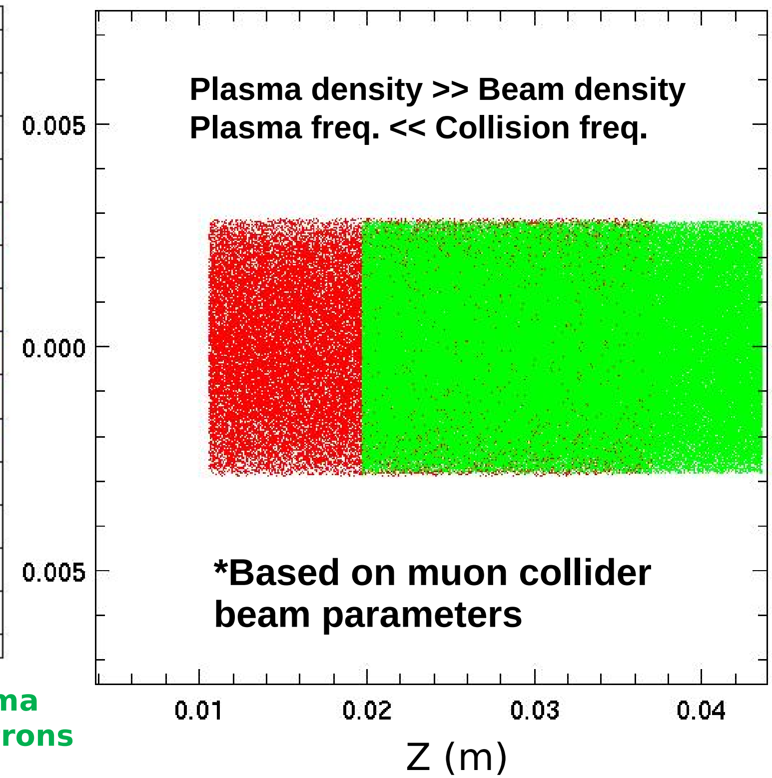
- Beam creates a column of plasma along the beam path
- Dynamics of the beam-plasma interaction are different than those of plasma wakefield accelerators
- Electrons have a limited mobility due to the high density, and so are not “blown” away by the beam



Wakefield accelerator



HPRF



- Work in progress
- Does not include all the necessary physics processes

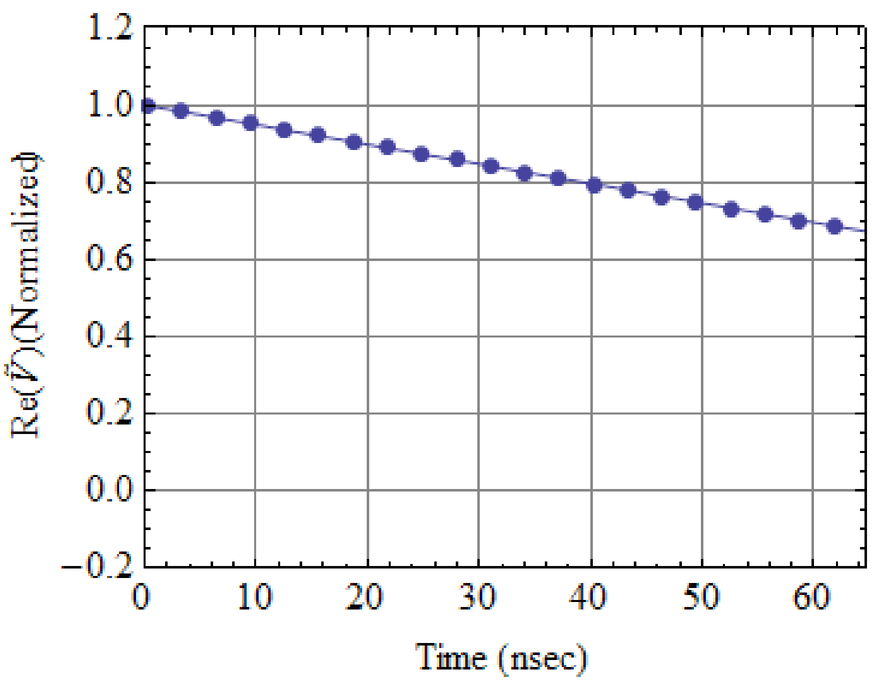
[Preliminary results using WARP code courtesy of M. Chung]

Beam Loading

- Intense muon beam induces image charges on the cavity surface, and results in additional voltage opposite to the accelerating voltages
- Circuit analysis with high quality factor in simple pill-box geometry:

$$V_b \approx -2kq_b\left[\cos\left(\omega_0 t\right)\right]$$

$$k = \frac{\omega_0}{4}\left[\frac{R}{Q}\right] = \frac{\omega_0}{4}\frac{(E_0 l_{cav} T)^2}{\omega_0 \frac{1}{2}\varepsilon_0 E_0^2 \pi R_w^2 l_{cav} J_0'(j_{0,1})^2} \qquad T = \frac{\sin[\omega_0 l_{cav}/2\beta c]}{\omega_0 l_{cav}/2\beta c} \qquad \omega_0 = \frac{j_{0,1}}{R_w}c$$



Synchrotron phase: 140°
Gas pressure + Be window: 160 atm at room temp + 60 μm
Transit time factor: 0.977
Bunch length: 100 ps (delta function for this calculation)
Number of bunches = 21
Total muons= 10^{13}
Frequency = 650 MHz
Bunch spacing = 3.1 nsec
E0 = 20 MV/m
lcav = 27.0 mm
R/Q = 34.4 Ohm

[Courtesy of M. Chung]

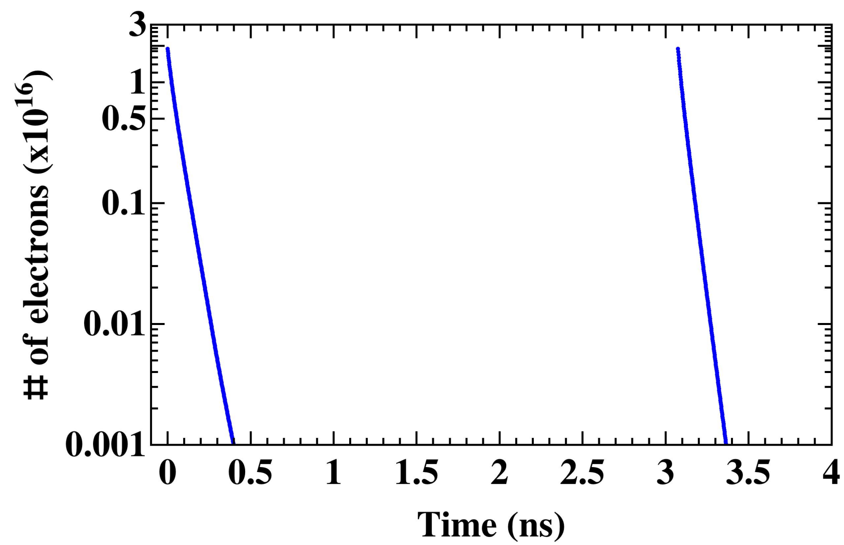
- ~30% drop in the net accelerating voltage (No HOM included)
- Not specific to HPRF cavities

Plasma Loading Calculation

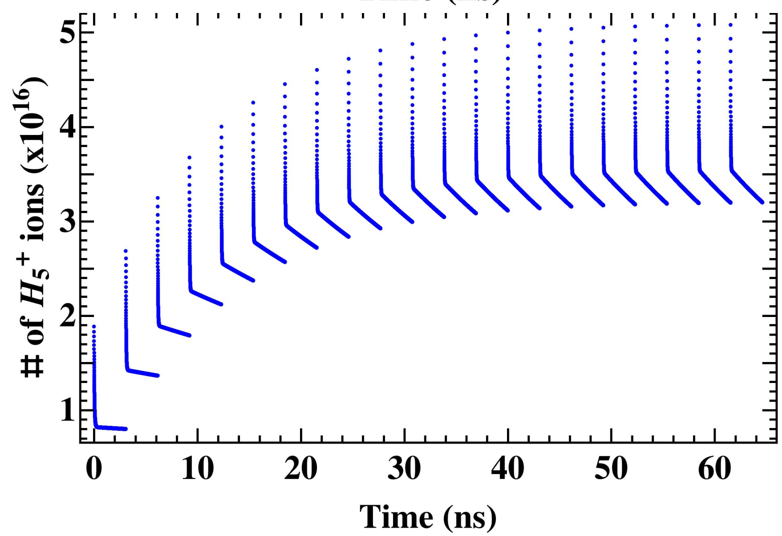
- A rough calculation of the expected plasma loading in an actual HCC can be done
- Input parameters (derived from beam test data):
  - Electron attachment time
  - Electron – hydrogen recombination rate
  - Hydrogen – oxygen recombination rate
  - Electron drift velocity (constant)
  - Ion energy loss
- Assumptions:
  - 325 MHz bunched beam
  - 21 delta function bunches
  - 160° injection (relative to RF)
  - 20 MV/m peak E field
  - 180 atm H_2 gas with 1% DA
  - 10 cm long cavity
  - Recombination rates constant (10^{-6} cm^3/s e-H, 10^{-9} cm^3/s O-H)
  - 1 cm^3 plasma volume (homogeneous density)
  - Attachment time varies with E field (100 ps min.)
  - Cavity voltage not affected by plasma loading

Plasma Loading Results

- The total number of each charged particle species is tracked over 21 beam pulses
- Electrons "decay" very quickly, however ions build up over time
- Time step is 1/1000 of an RF period
- 650 MHz RF, 10^{12} μ/bunch is shown on right
- ***No significant plasma loading is observed***



Parameter	Unit	Value			
RF frequency	MHz	325		650	
Stored energy	J	19		4.7	
μ/bunch	#	10^{11}	10^{12}	10^{11}	10^{12}
Electron dissipated energy	J	0.014	0.072	0.012	0.062
Ion dissipated energy	J	0.010	0.029	0.020	0.059
Total dissipated energy	J	0.024	0.101	0.032	0.121
% of V_{accel} seen by last bunch	%	99.9	99.7	99.7	98.7

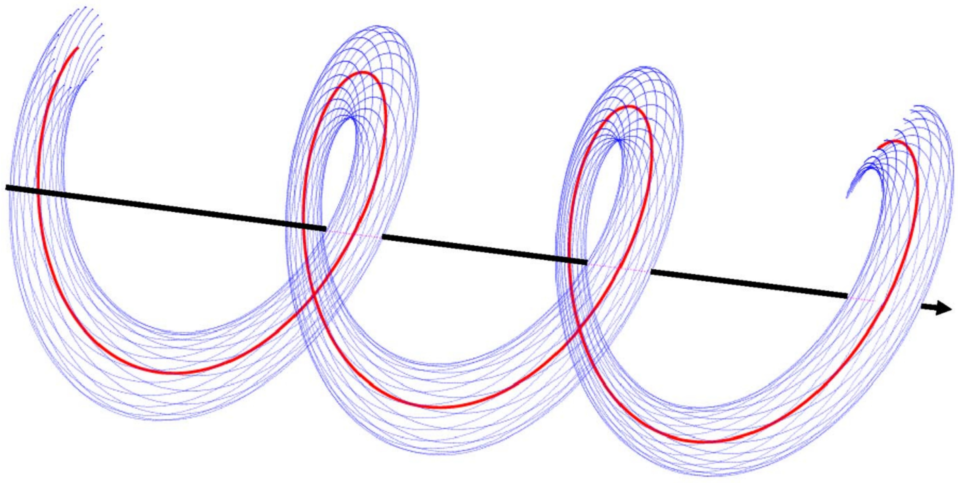


Putting It All Together

- Predicting the plasma loading in an actual cooling channel is a challenging endeavor
  - The interaction of 10^{12} muons with the gas and the resulting plasma evolution must be modeled on the picosecond timescale for the duration of microseconds
  - Beam loading and space charge must be considered in calculating the real electromagnetic fields within the cavity
  - Range of beam sizes and cavity geometries/frequencies to consider
- The results obtained at the MTA are a good start
- **Indications are that plasma loading should not significantly degrade the performance of a gas filled cavity**
- Proof-of-principle experiment is not likely to happen soon
- Rigorous simulation efforts are being pursued

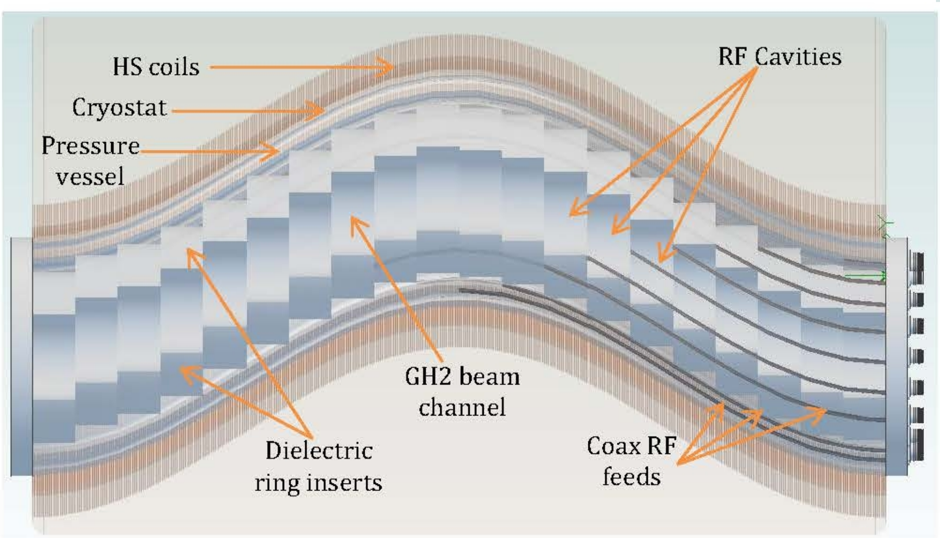
6D Cooling

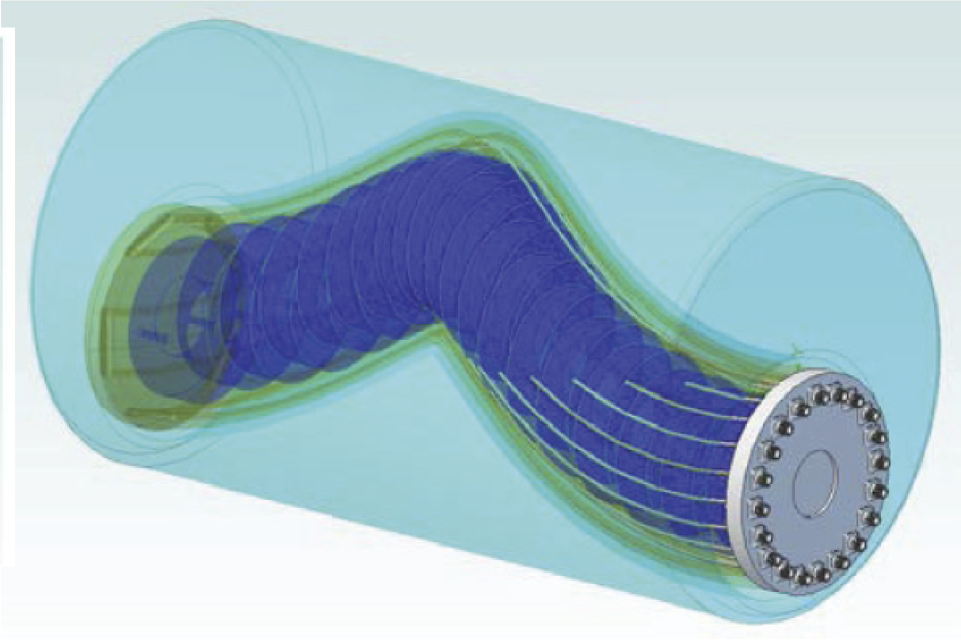
- Ionization cooling intrinsically works on the transverse components
- To cool longitudinally, dispersion must be incorporated
- If higher momentum particles are forced to traverse more absorbing material (and lower momentum less), the energy spread of the beam will decrease
  - This is achieved by incorporating a complex magnetic field
- The result is that particles travel along a helix



Helical Cooling Channel

- Arrange a configuration of magnets such that solenoidal and helical dipole and quadrapole fields exist
- Place homogeneously distributed H_2 filled RF cavities along the particle orbit
- Ionization cooling provided by the gas and RF cavities with dispersion from the magnets produces continuous 6D cooling



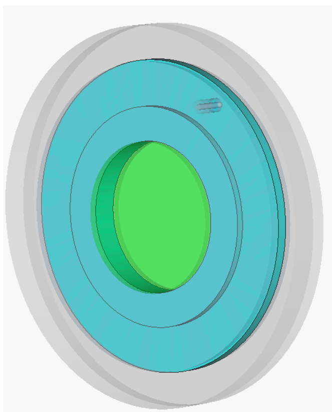


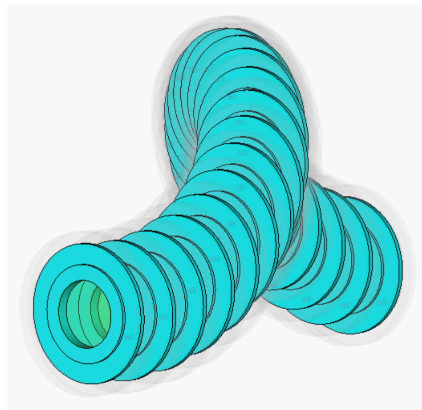
Engineering Challenges

- There are essentially two components to a HCC
  - RF cavities / power sources
  - Magnets
- Separately, they are not particularly challenging
- Combining the two into something that can be built, is, however
- Magnetic fields beginning at 4 T and increasing to 14 T are required
  - Small bores
- Current RF frequencies are 325 and 650 MHz
  - Transverse size must be shrunk to fit within magnets
- Adding waveguides, plumbing, instrumentation and diagnostics complicates matters

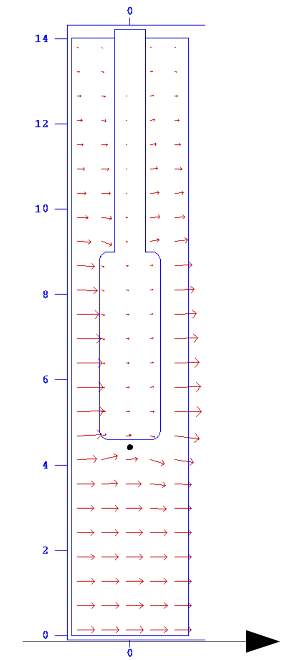
Dielectric Loaded Cavities

- Placing a ceramic disc at a large radius (small E field) shrinks the radius based on the dielectric constant (ε = 9.3 ~factor of 2)
- Loss tangent of the dielectric material must be considered





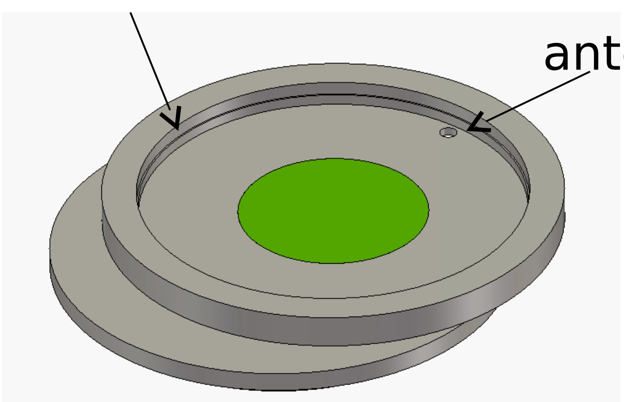
Example:
f = 650 MHz
r = 140.1mm @ ε = 9.3
R/Q @ β = 0.884
(pμ=200 MeV/c)
ceramic: Al2O3
Lact = 27.3 mm (HCC segment 5)



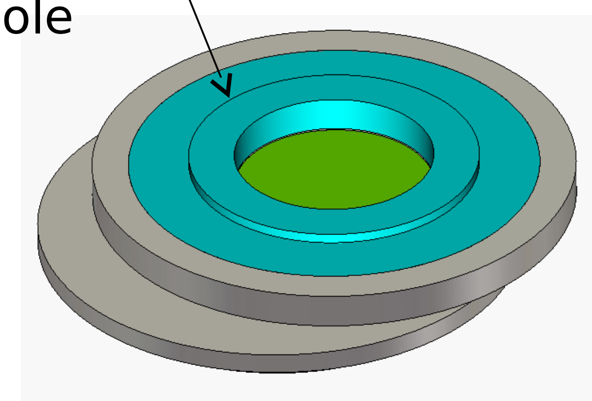
Beam

recess to hold ceramic (~1mm)

antenna hole



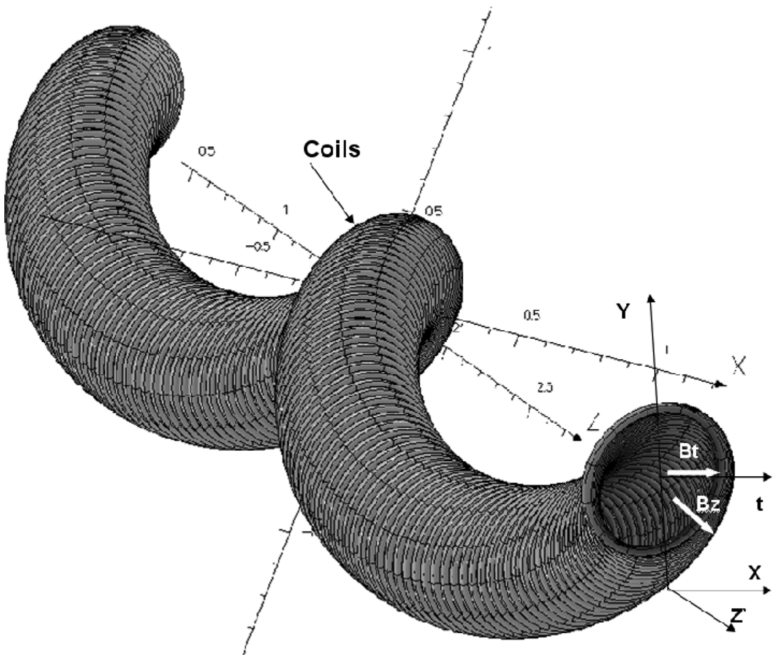
ceramic placed inside



[Courtesy of F. Marhauser]

Magnet Progress

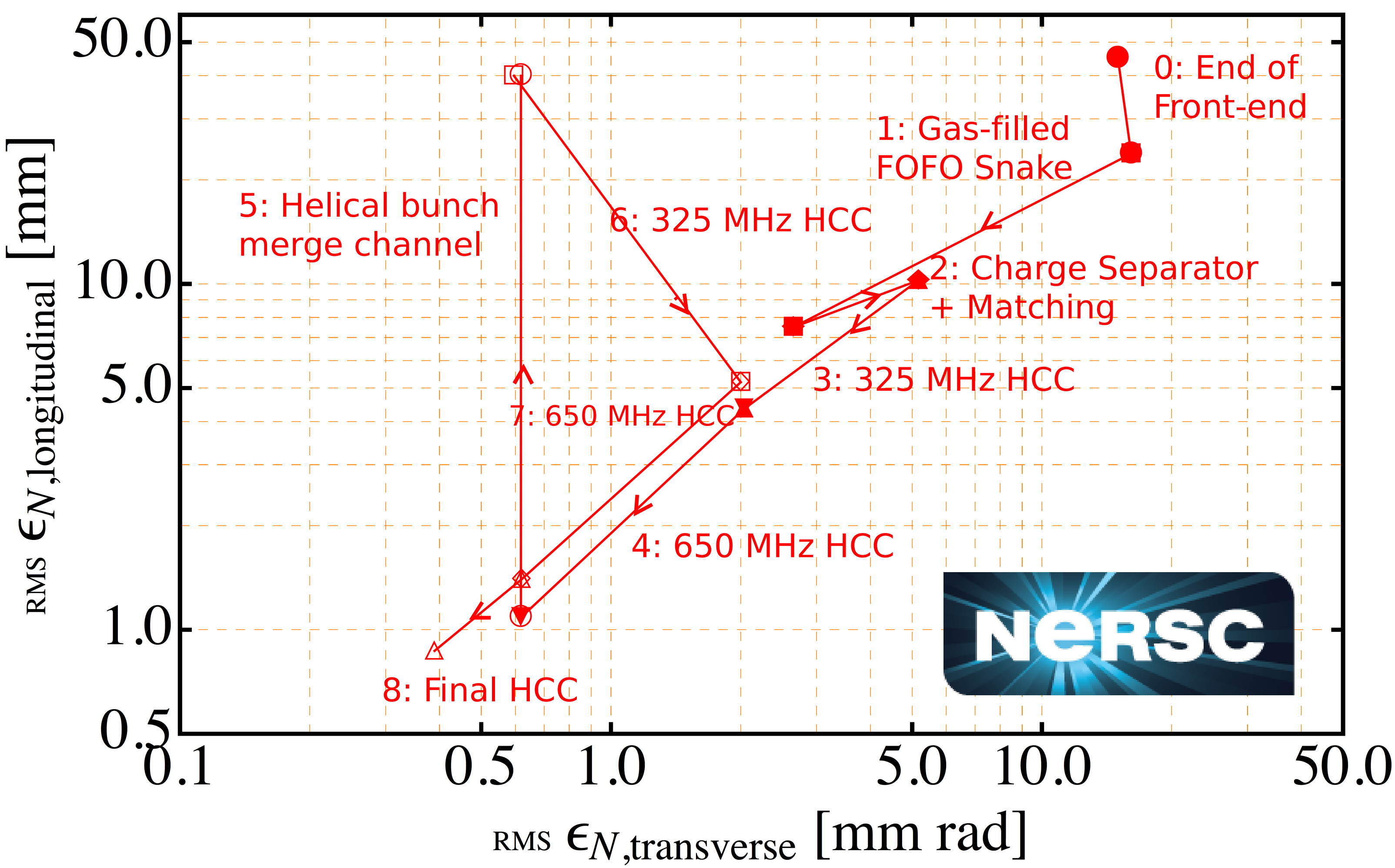
- A helical solenoid magnet system provides the required fields (longitudinal solenoidal, transverse helical dipole, and helical quadrapole)
- Coil planes are normal to the z axis, not the equilibrium orbit
- Helical solenoids have been tested:
  - Prototypes were built along the past 5 years
    - NbTi (2 models, 4 coils each).
    - YBCO Tape (3 double pancakes).
  - The coils performed well.
  - A Nb3Sn model is in development.

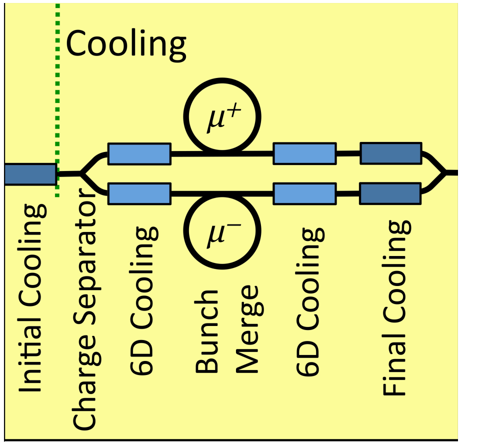


V. Kashikhin et al, IEEE Trans. Appl. Superconduct., 18(2), 2008

[Courtesy of M. Lopes]

Cooling Channel Simulation – I

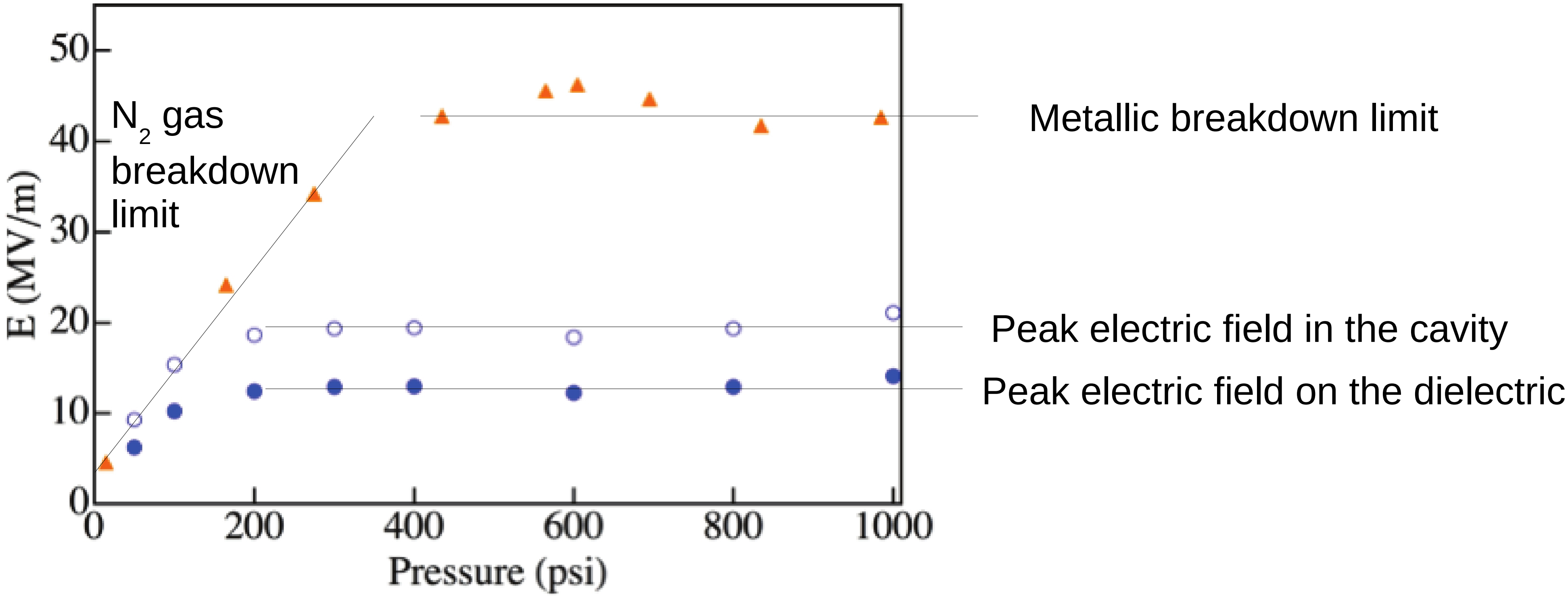




[Courtesy of K. Yonehara]

High Power Dielectric Tests

- Alumina (Al_2O_3) has been tested and found to have a dielectric strength of 14 MV/m, with a loss tangent of 10^{-4}
- Other materials are being investigated, and a beam test is scheduled to observe the effect of charge accumulation on the dielectric



L. Nash et al, Proceedings of IPAC '13, TUPFI068

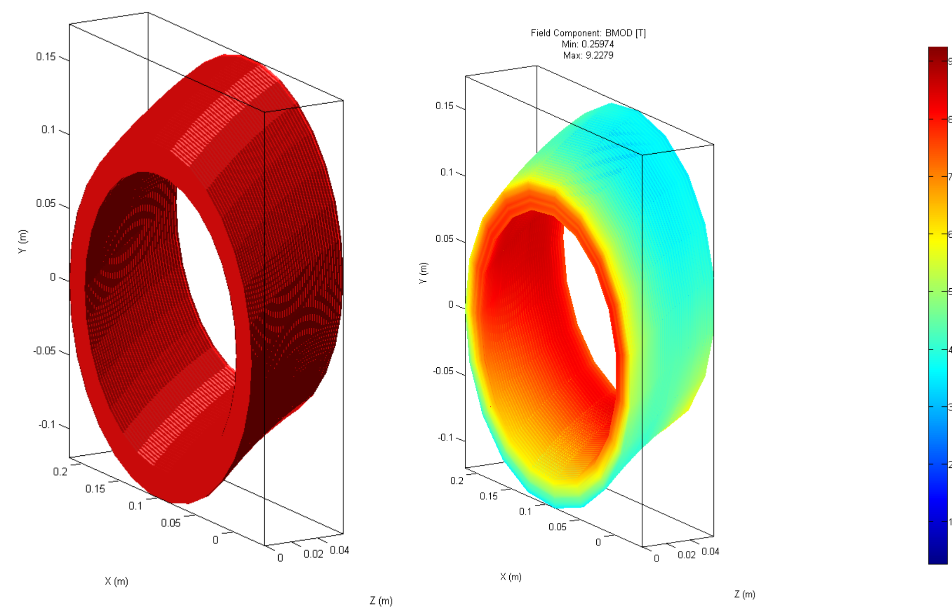
Nb3Sn Prototype

- Fabrication in progress
- Provides continuous coil geometry
- 10 T design

Parameter	Unit	Value
Coil Inner diameter	mm	200
Helix period	mm	600
Orbit radius	mm	95
Coil length	mm	60
Number of turns per layer		40
Number of layers		2
Insulated cable thickness	mm	1.5
Insulated cable width	mm	10.25

R.P. Johnson et al, Proceeding of COOL 13, MOAM2HA03

[Courtesy of M. Lopes]



Remarks

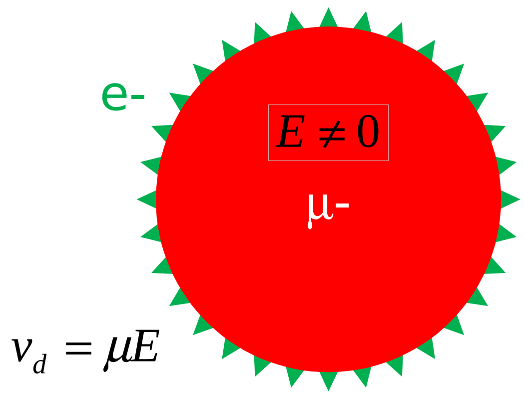
- A great deal of progress has been made on designing a gas filled cooling channel for a Muon Collider
  - All indications show that HPRF cavities will work in a cooling channel
- Simulation efforts are underway to fully predict the effects of interactions between the plasma, gas, and beam
- The results of the beam test at the MTA allow a full scale engineering design of a helical cooling channel to progress

Backup slides

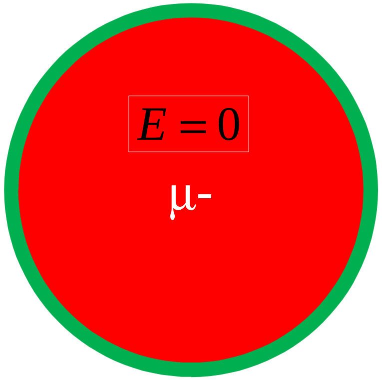
Beam – Plasma II

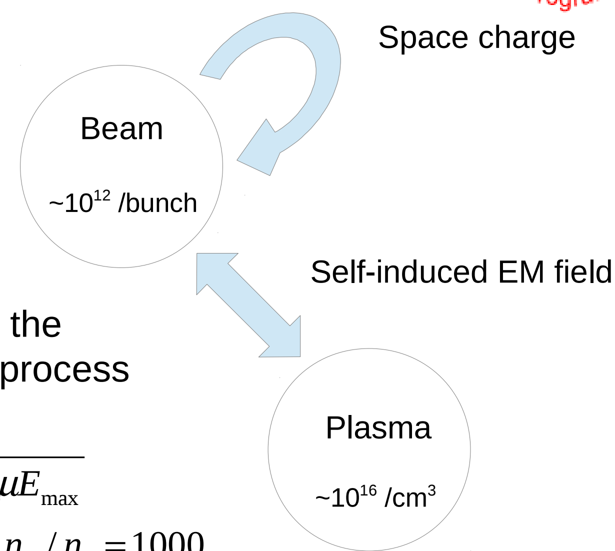
Space charge neutralization can occur

Space charge of the muon beam pushes electron outward



Electron column expands slightly, making E-field inside the beam vanish

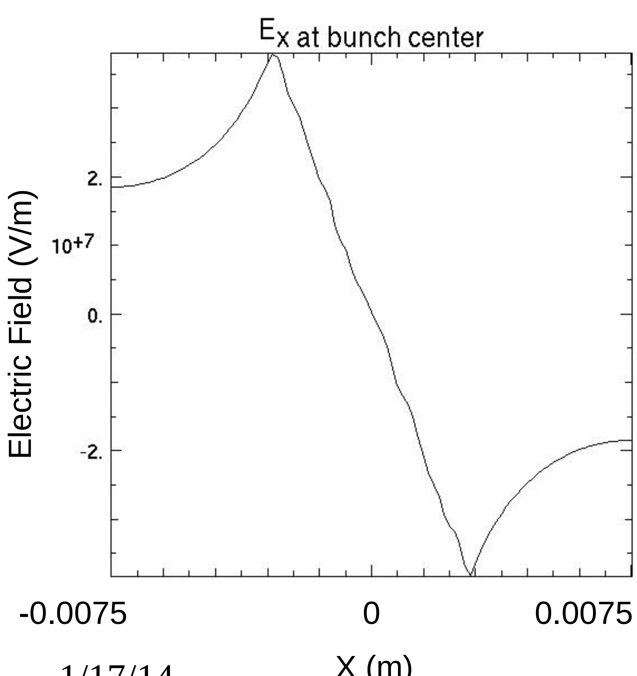


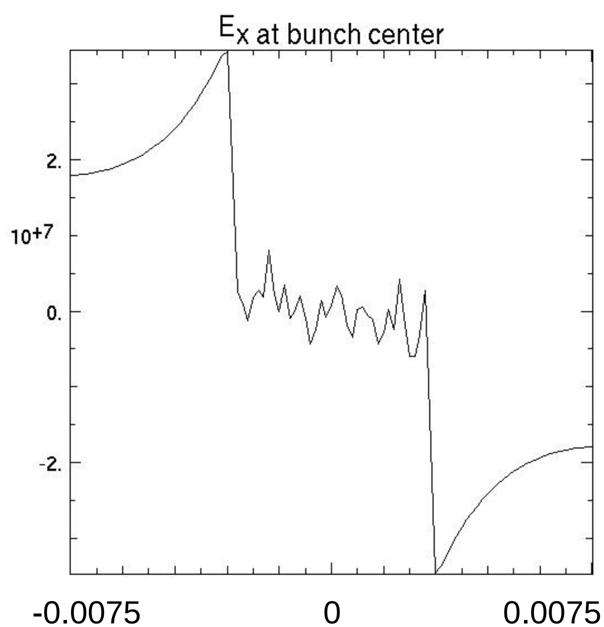


Time scale for the neutralization process

$$\tau_{SCN} \sim \frac{r_b}{2(n_p/n_b)\mu E_{\max}}$$

~ 40 ps for $n_p/n_b = 1000$





Other time scales:
- Bunch length ~ 100 ps
- Electron removal by attachment to O2 ~ 0.5 ns
- Bunch spacing = 3.1 ns, Pulse length = 60 ns
- Plasma removal by ion-ion recombination > 100 ns

WARP simulation reproduces the neutralization process:

$$\tau_{SCN} \sim 15 \text{ ps for } n_p/n_b = 1000$$

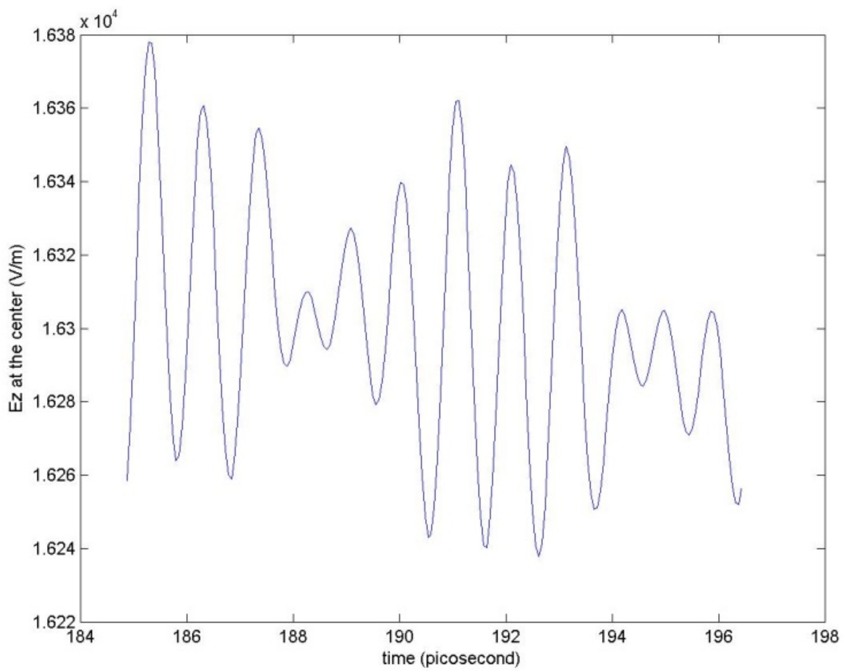
Issues to be addressed:
- Numerical noise
- Any change in net focusing of the beam ?
- Different neutralization degree between head and tail
- Effect of electron attachment to O_2

[Preliminary results using WARP code courtesy of M. Chung]

Simulation Results – I

- A group at BNL and SUNY Stony Brook have begun incorporating the plasma dynamics measured at the MTA with EM field calculating routines in a hybrid PIC code called SPACE to study how the beam, neutral gas, and plasma interact

[Courtesy of K. Yu]



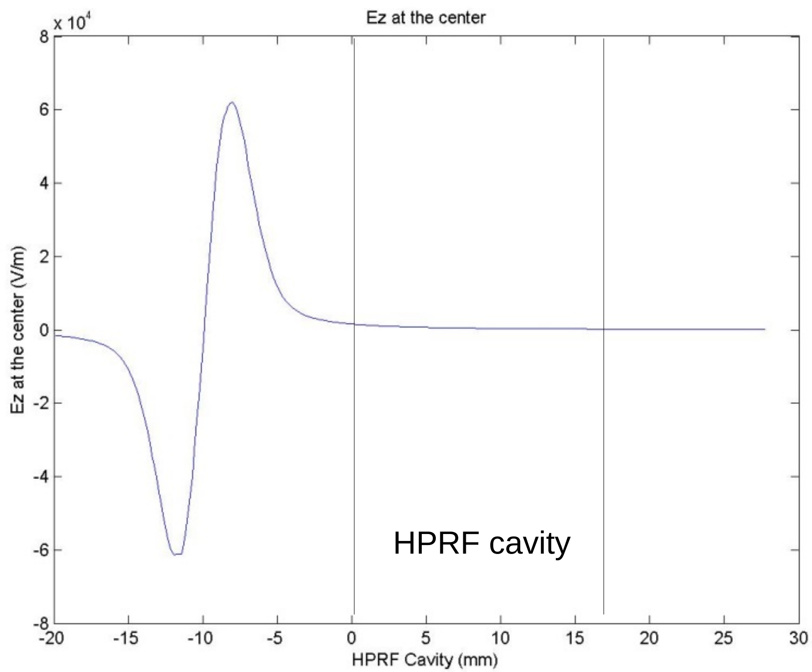
Beam-induced E_z near the center of the HPRF cavity after beam passage

Parameter	Units	Value
Kinetic Energy of Beam	MeV	400
Initial Velocity of Beam	m/s	2.137e+8
β		71.292
H2 Gas (Mass) Density	g/cm3	0.00867
H2 Gas (Number) Density	#/cm3	2.59
dE/dx	MeV cm2 / g	6.332
W (Average Ionization Energy)	eV	36.2
Electric Field	MV/m	20
Magnetic Field	T	3
Bunch Population	# / bunch	2e+8

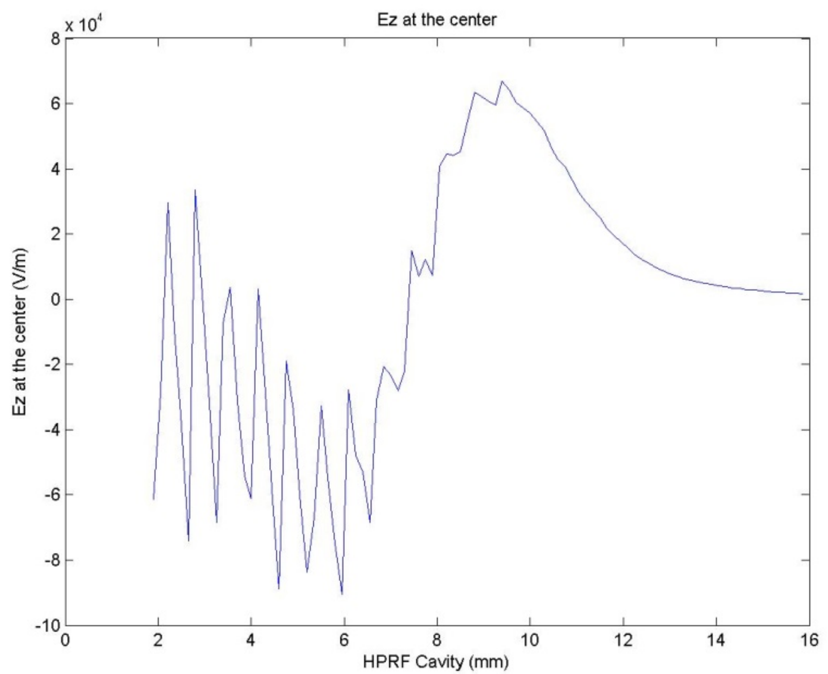
Simulation Results – II

- Beam-induced E_z at r = 0 before and after passage of the beam

[Courtesy of K. Yu]



t = 0 ps



t = 82.6 ps

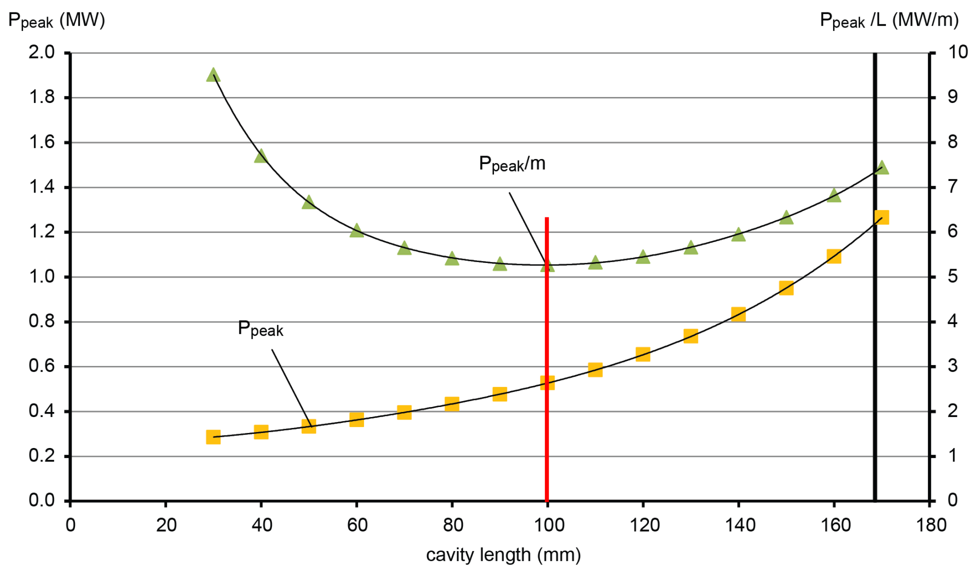
RF Options

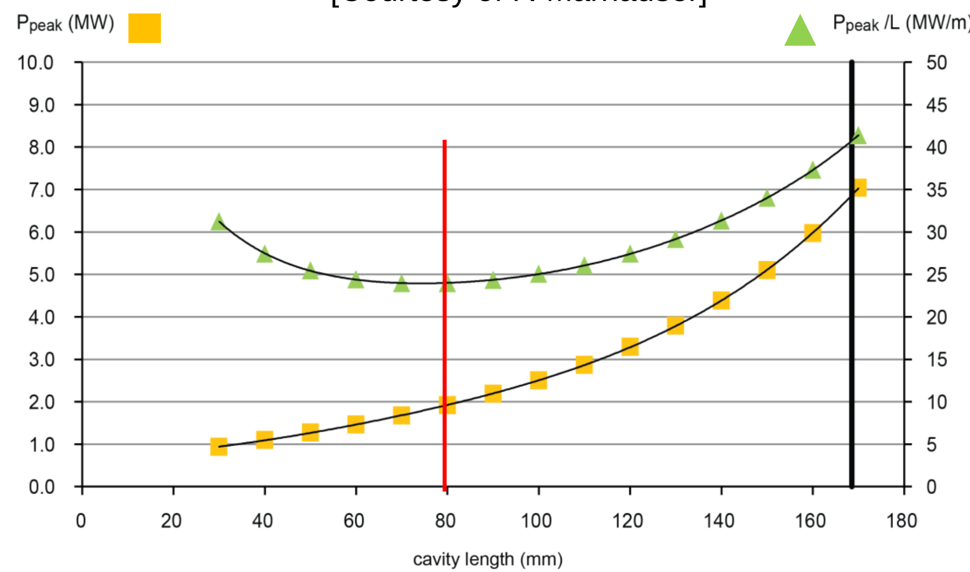
- The radial size of the cavities must be shrunk to fit within the magnets
- Two options are being pursued in order to accomplish this
  - Dielectric loaded cavities
  - Reentrant cavities

Power Considerations

- Filling a cavity with dielectric increases peak power and peak power per unit length

[Courtesy of F. Marhauser]





No ceramic
P_{peak} = 0.5 MW per cavity
P_{peak}/L = 5 MV/m

$\varepsilon = 9.3$, $\tan \delta = 0$
P_{peak} = 2 MW per cavity
P_{peak}/L = 25 MW/m

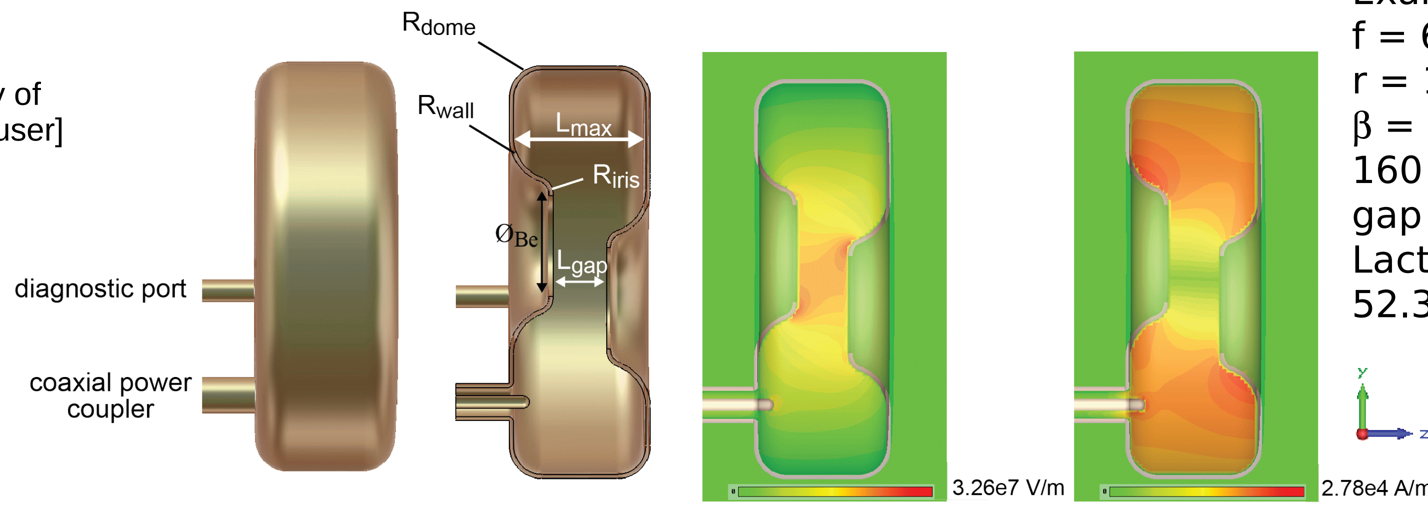
- Materials with low loss tangents and high dielectric strengths (10-20 MV/m) are being investigated

Reentrant Cavities

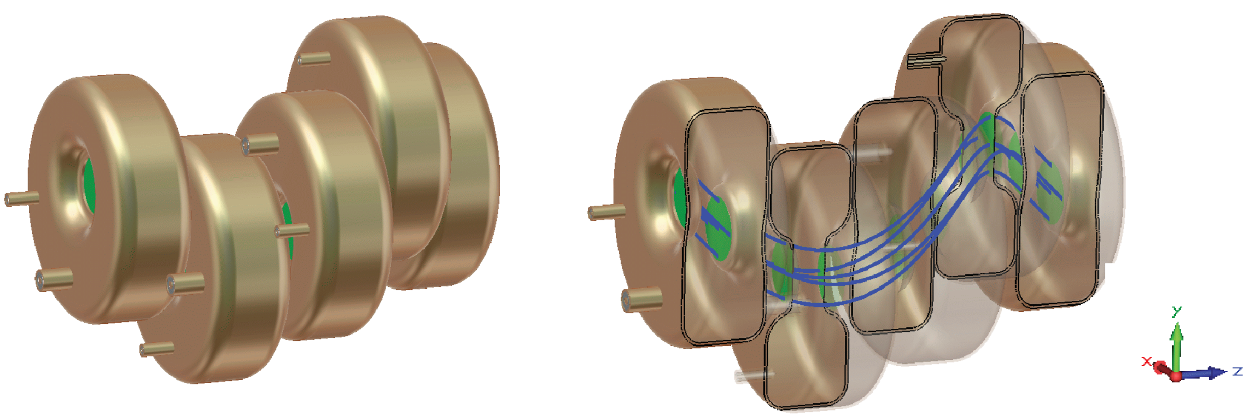
- Making the cavities reentrant will also shrink the size
- Terminated with Be windows

Example:
f = 650 MHz
r = 140.1 mm
β = 0.884 (pμ=200 MeV/c)
160 atm GH2
gap = 37 mm (segment 5)
Lact = gap * Sqrt(2) =
52.33 mm

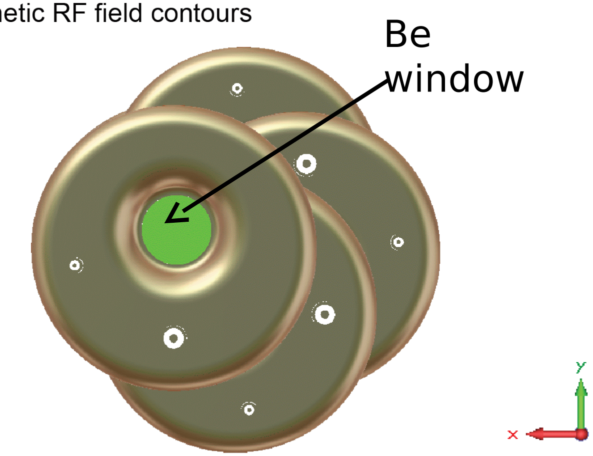
[Courtesy of F. Marhauser]



side view   cross section   electric RF field contours   magnetic RF field contours



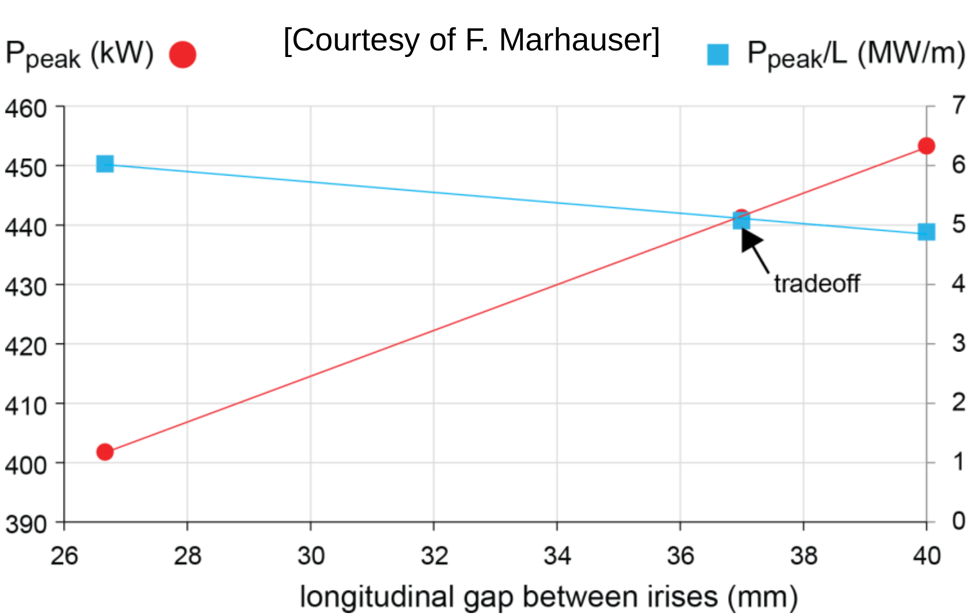
perspective views

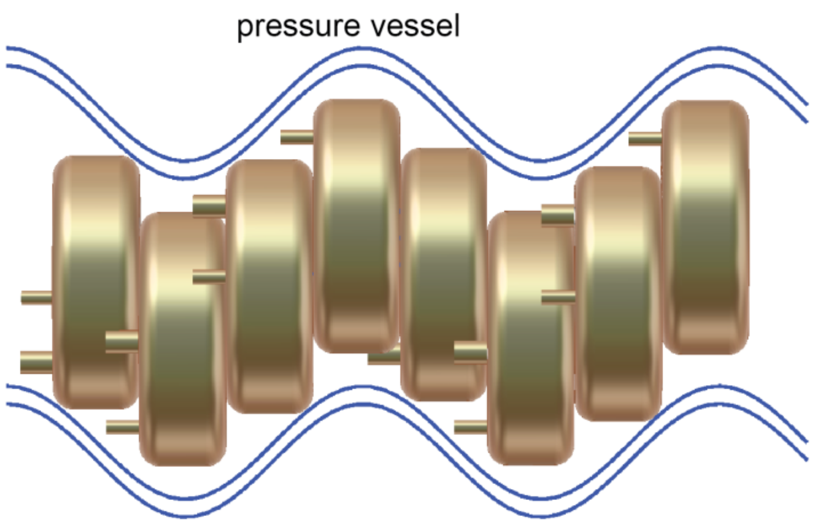


front views

Power Considerations

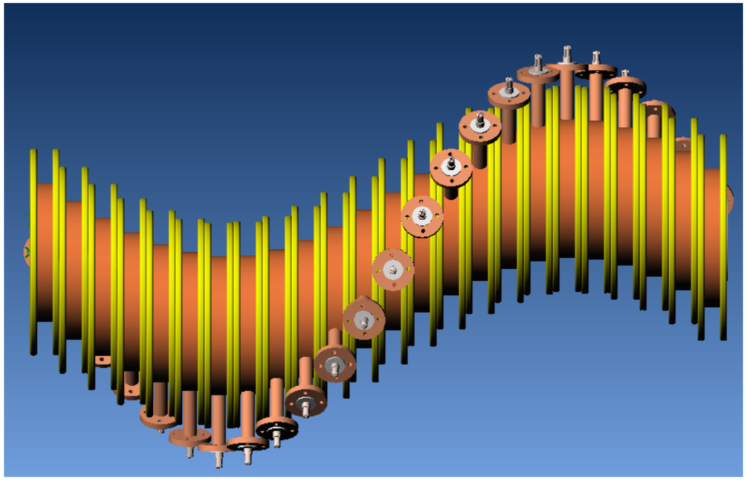
- P_{peak} = 0.5 MW, P_{peak}/L = 4.4 MW/m (4x and 6x smaller)
- Number of cavities per period is reduced

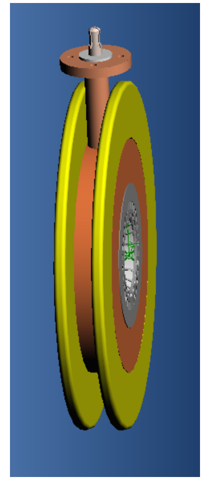


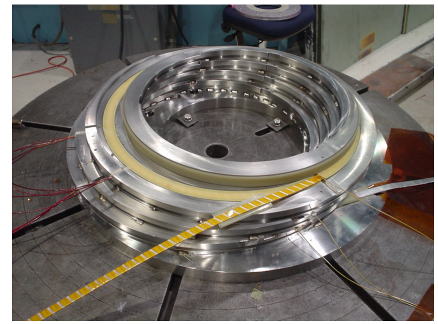


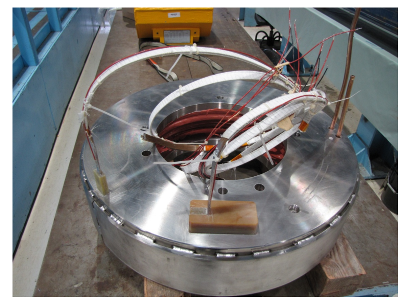
2 periods, 4 cavities per period

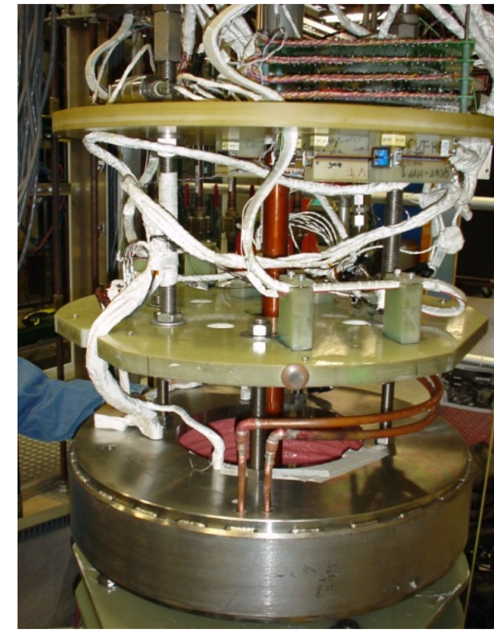
NbTi Prototype











[Courtesy of M. Lopes]

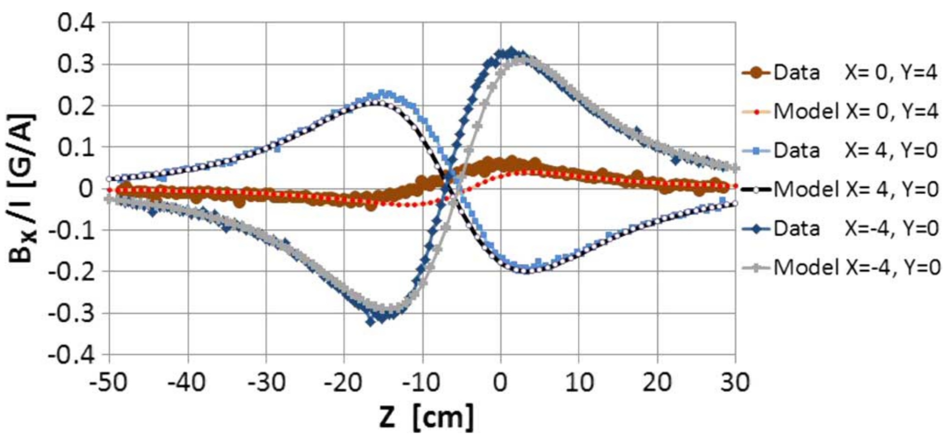
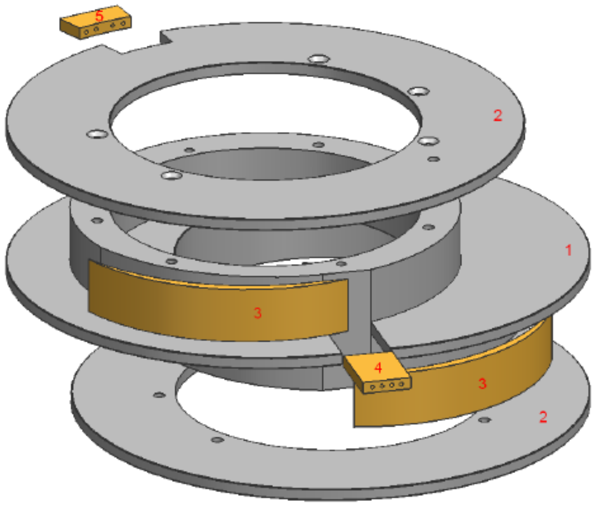


Fig. 4. Comparison of HSM01 transverse (B_x) field magnetic model and measurement.

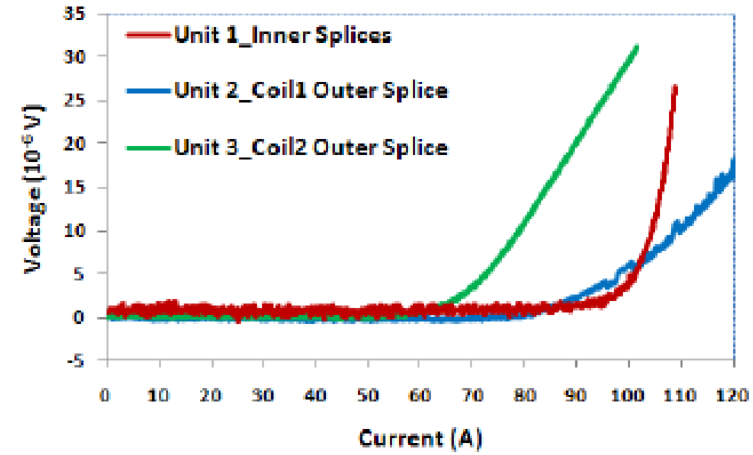
5 T achieved

N. Andreev et al, IEEE Trans. Appl. Supercond., 22 (2012) 4101304

YBCO Tape Prototype

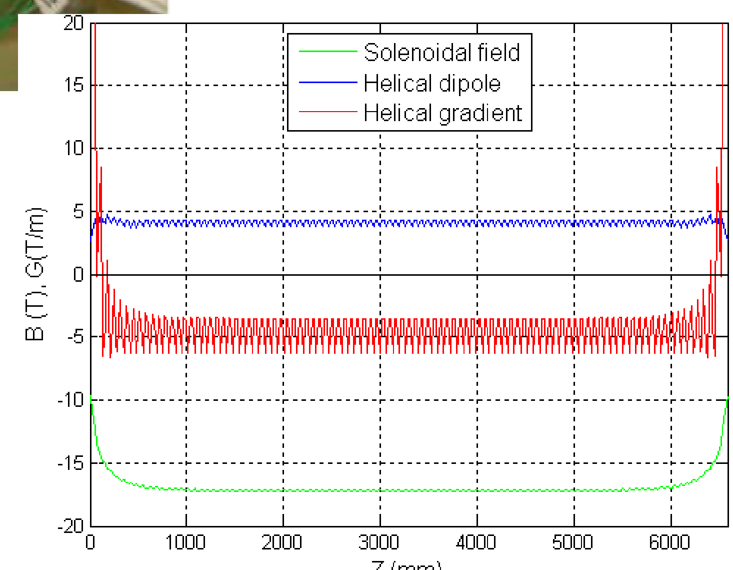


[Courtesy of M. Lopes]



M. Yu et al, Proceedings of PAC 11, TUP153

16 T achieved

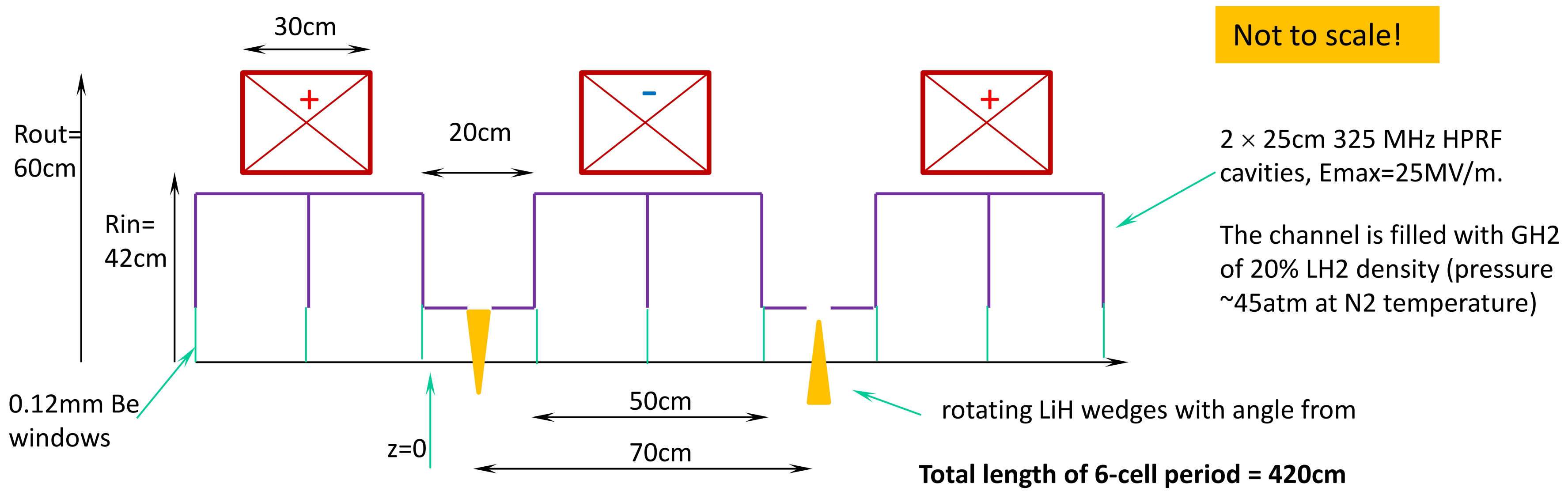


Parameter	Unit	Value
Section length	m	40
Helix period	m	0.43
Orbit radius	m	0.068
Solenoidal field, B_z	T	-17.3
Helical dipole, B_t	T	4.06
Helical gradient, G	T/m	-4.5 (1.4)
Coil radial thickness	mm	210
Coil longitudinal thickness (HTS YBCO tape width)	mm	16
Inner diameter	mm	100

Initial Cooling

- In addition to the HCC, a FOFO Snake is being investigated
- Variant of the vacuum channel design, uses tilted solenoids and wedge absorbers to provide cooling

[Courtesy of Y. Alexahin]



Final/Initial values (Gaussian fit):

	$N^{(150<p<360)}$	$N^{(core)}$	$p^{(cnt)}$, MeV/c	ε_{mN}, cm			ε_{6D}, cm^3
μ^+	5161/7998	4927/7329	208.8/248.0	0.18/1.19	0.39/2.19	0.75/2.38	0.051/6.22
μ^-	5672/9020	5495/8248	209.5/248.8	0.17/1.22	0.46/2.10	0.74/2.19	0.058/5.59

Cooling Channel Simulation – II

[Courtesy of K. Yonehara]	L	Trans-mission	Initial εT/Final εT	Initial εL/Final εL	Initial ε6D/ Final ε6D	Gas P @ 300 K	Ez***	Bz on beam
	m		mm rad	mm	mm3	atm	MV/m	T
1: FOFO Snake	100	0.7	16.1/ 2.65	23.8/ 7.5	6.22 106 / 5.1 104	170 45@80 K	25	3.85
2: Adiabatic matching	2	0.99 (0.6 in 325 MHz HCC)	2.65/ 5.17	7.5/ 10.25	5.1 104/ 1.21 105	43#	20	2.7 → 5.6 → 4.9
3,6: 325 MHz HCC*	100?	0.88?	3.77/ 1.02?	15.6/ 4.80?	1.2 105/ 20?	160 43@80 K	20-27?	4.9 → 5.3
4,7: 650 MHz HCC	120	0.8	2.04/ 0.618	4.36/ 1.09	14.8/ 0.295	160 43@80 K	20	8.5
5: Helical bunch merge**	105	0.88	0.618/ 0.618	1.09/ 40.0	0.295/ -	0 (43)	1@204-272 5@201 MHz	4.9
8: Final HCC	80	0.9	0.618/ 0.390	1.09/ 0.87	0.295/ 0.0945	160 43@80 K	20 @975 MHz	10.7

~25% Transmission – acceptable

* 325 MHz HCC lattice design is in progress (values are from past result here)

** Values for helical bunch merge is evaluated in a 201 MHz base channel

*** Use Be RF window except for final HCC (120 μm for 325 MHz, 60 μm for 650 MHz)

- Cooling by using practical fields was also evaluated and the result were very similar as the analytical one (see backup)
- Matching is not fully optimized.
- Initial particle dist. in a 650 MHz HCC is generated to fill its phase space via the following procedure:

  Particles with large emittance are transported in the 650 MHz HCC w/o stochastic processes.

  Initial kinematics of particles surviving 20 helix periods are used in the evaluation of the 650 MHz HCC w/stochastic processes on.

Thermalization Time

$$\tau_e = \frac{1}{\zeta_e \, \nu_e}$$

$$\nu_e = 60 \times 10^{12} \; s^{-1}$$

$$\zeta_e = 10^{-3} - 10^{-2}$$

(rotational, vibrational, elastic collisions)

$$\tau_e = 1.7 - 17 \; ps$$